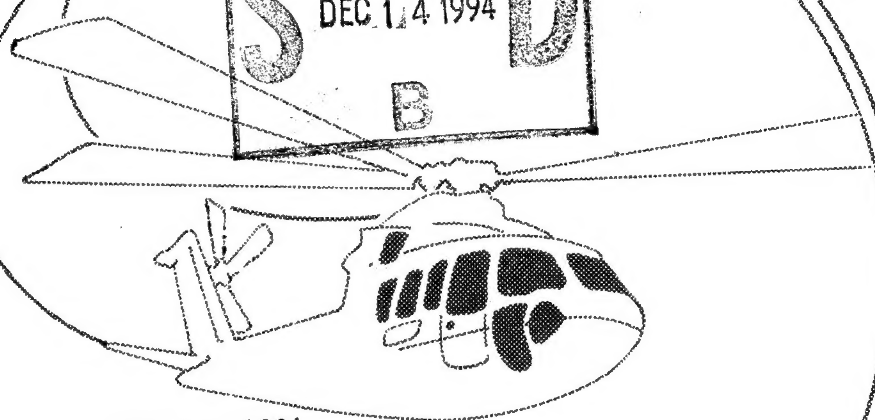
DOT/FAA/CT-91/7

FAA Technical Center
Atlantic City International Airport,
N.J. 08405

Rotorcraft Crashworthy Airframe and Fuel System Technology Development Program



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Final Report

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16. Abstract

A research program was initiated by the Federal Aviation Administration (FAA) Technical Center to investigate crash resistance design technology applicable to U.S. civil rotorcraft. The purpose of the program was to identify crash resistance design technology consistent with rotorcraft type, primary use, and the expected crash environments for civil helicopters. The program examined crash resistance technology for landing gear, fuselage structure, seating systems, and fuel systems. A trade-off study was conducted to identify an optimum level of crash resistance for three weight classes of civil rotorcraft. The results of the research program were a series of crash impact design and test criteria for civil rotorcraft, as well as an assessment of the weight penalties that would be incurred in meeting these criteria. The program was conducted by Simula Inc. with assistance from Bell Helicopter Textron Inc. and Sikorsky Aircraft.

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PREFACE

The Simula Inc. Program Manager was J. W. Coltman. Engineering support for seat and aircraft design and trade-off analyses was provided at Simula Inc. by E. J. Racette, G. Yaniv, C. VanIngen-Dunn, L. W. Bark, and M. K. Richards.

Bell Helicopter Textron Inc. was responsible for the evaluation of crash-resistant airframe and landing gear technology. This work was conducted by J. D. Cronkhite and R. V. Dompka. Sikorsky Aircraft provided a similar role for crash-resistant fuel system technology. Work conducted at Sikorsky Aircraft was performed by B. L. Carnell and J. DeCarlo.

Technical assistance was provided by a number of equipment manufacturers in the evaluation of crash-resistant fuel systems. Assistance for the fuel cell technology review was provided by Loral Engineered Fabrics, Rockmart, Georgia; Uniroyal Plastics Company, Inc., Mishawaka, Indiana; FPT, Inc., Wilmington, North Carolina; and AM Fuel, Magnolia, Arkansas. Information on fuel line and valve technology was provided by the following manufacturers: Aeroquip Corporation, Jackson, Michigan; Spectrum Associates, Inc., Milford, Connecticut; and Symetrics, Inc., Newberry Park, California.

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EXECUTIVE SUMMARY

This research program was initiated by the Federal Aviation Administration (FAA) Technical Center to investigate crash resistance design technology applicable to the U.S. civil rotorcraft fleet. The purpose of the program was to identify crash resistance design technology consistent with rotorcraft type, primary use, and the expected crash environment for civil helicopters. In a previous study sponsored by the FAA Technical Center, a thorough investigation of the civil helicopter crash environment was undertaken; it formed the basis for identifying the expected crash conditions for the civil fleet. The research program described in this report is significant in that it comprehensively addresses appropriate levels of crash resistance for civil rotorcraft.

The approach taken in the study consisted of the following five tasks:

- Survey existing design and analysis technology for crash-resistant landing gear, fuselage structures, seats, and fuel systems.
- Examine the crash environment for civil rotorcraft to determine a realistic crash protection level.
- Prepare conceptual designs for crash-resistant systems that could be incorporated into rotorcraft representative of the civil fleet. Consider various levels of crash resistance in the completed designs.
- Conduct a trade-off study to obtain the optimum crash resistance level for civil rotorcraft considering the expected crash environment.
- Prepare recommended design and test criteria for future civil rotorcraft of crashworthy design.

The anticipated outcome of this effort was the identification of levels of crash protection that could realistically be incorporated into future civil rotorcraft without excessive weight and cost penalties.

The survey of crash protection technology identified both strengths and weaknesses in the existing technology base. The survey examined analytical, design, and testing methodologies, as well as validation of these methodologies. A strong technological base was found to exist in aircraft, seat, and occupant analysis; knowledge of human tolerance to acceleration and impact injuries; energy-absorbing seat design; and materials and structures for energy-absorbing subfloors. Weaknesses were identified in the following areas of the technological base: landing gear with enhanced energy absorption for civil rotorcraft; validation of lightweight crash-resistant fuel system (CRFS) concepts; effect of water impact on crash survivability; innovative, low-cost approaches for structural energy absorption; and, in general, crash resistance technology applicable to small rotorcraft of gross weight less than 2,500 lb.

The crash environment data developed in the previous FAA-sponsored program were reexamined to define realistic levels of crash protection that could be justified by the potential reduction in injuries and fatalities. Three significant findings from the earlier study were reaffirmed:

- The typical impact conditions for U.S. civil rotorcraft are substantially less severe than for U.S. military rotorcraft
- A large percentage of civil rotorcraft accidents are potentially survivable
- The predominate hazards to occupant survival were, in order of importance, post-crash fires, seat failures, restraint system failures, and drowning.

The potential for occupant survivability in the current civil helicopter fleet was examined. It was found that vertical impact velocity had the most significant effect on survivability. For the current civil fleet, a vertical impact velocity of 30 ft/sec was the approximate transition point from potentially survivable to nonsurvivable. However, even though the accidents were potentially survivable, a significant number of serious injuries and fatalities occurred. Approximately 11 percent of the occupants in these survivable accidents received serious injury and 6 percent received fatal injuries. An analysis was conducted to determine the impact levels at which the serious injuries and fatalities occur, and it was found that a disproportionate number of these severe injuries occurred in a range of impact velocities below the survivability limits for the aircraft. Even though only 10 percent of the occupants were involved in crashes in this range, their injuries resulted in 34 percent of the injury costs*. From this analysis, it was clear that the greatest benefit from increased crash protection was realized at velocities below the maximum survivability limit for the rotorcraft fleet. This analysis indicated that significant reductions in occupant injuries could be achieved if crash protection levels of civil rotorcraft were designed for the following impact velocities:

- Vertical (downward): 26 ft/sec
- Longitudinal (forward): 50 ft/sec
- Lateral: 10 ft/sec.

Three generic rotorcraft designs were prepared to assess the effect of incorporating increased levels of crash protection. The conceptual rotorcraft designs included drawings of the overall configuration and structural, seat, and fuel system designs. The goal in preparing the designs was to provide a basis for examining actual component designs that would provide varying levels of crash protection.

A trade-off analysis was conducted to examine the weight penalty associated with varying levels of crash protection. The baseline for this analysis was the three generic rotorcraft models with equipment designs which would meet the current Federal Aviation Regulation (FAR) requirements. Four higher levels of crash protection were examined for each of the three generic rotorcraft. The primary variable in this analysis was the vertical impact velocity. The four higher levels of crash protection which were examined were: 14 ft/sec, 20 ft/sec, 26 ft/sec, and 32 ft/sec. The weight penalty for each crash-resistant component or system was established at the baseline and the four higher levels of crash protection. The result of the trade-off analysis was a relationship between crash protection level and weight penalty for each of the generic rotorcraft. At the 26 ft/sec vertical impact velocity level, which was identified as the optimum protective level for civil rotorcraft, weight penalties of 2.4 percent to 3.6 percent of gross weight could be expected, depending on rotorcraft size. It is believed that weight penalties of this magnitude can be accommodated, although it is apparent that the smaller weight classes carry a higher penalty to achieve the same level of crash protection.

*Injury costs were based on projected values for medical costs and court settlements which were established by the FAA for cost/benefit analyses.

The work that was conducted to identify the appropriate crash protection levels and the understanding that was gained through development of crash-resistant systems for the three generic rotorcraft led to the formulation of design and test criteria. The criteria that were developed covered overall aircraft impact criteria as well as component criteria. Design and test criteria were developed for landing gear, fuselage subfloor structures, seating systems, high-mass item retention, and fuel systems. The criteria that were established for seating systems were consistent with dynamic performance criteria defined in the recently enacted rule changes to FAR Parts 27 and 29.

1.0 INTRODUCTION

This research program was initiated by the Federal Aviation Administration (FAA) Technical Center to investigate crash resistance design concepts applicable to the U.S. civil rotorcraft fleet. The purpose of the program was to identify crash resistance design technology consistent with aircraft type, primary use, and the expected crash environment for civil helicopters. In a previous study sponsored by the FAA Technical Center, a thorough investigation of the civil helicopter crash environment was undertaken (Reference 1) and it formed the basis for identifying the expected crash conditions for the civil fleet. The goal of the current program was to examine the civil rotorcraft accident and injury statistics, and define a realistic level of crash protection. The outcome of this work is a set of defined design and test criteria that would lead to improved crash protection in the civil rotorcraft fleet without imposing unwarranted weight and cost penalties.

The research program described in this report is significant in that it is one of the first to address crash resistance for civil rotorcraft. Numerous design and test methodologies for military aircraft have been developed under the sponsorship of the U.S. Army (compiled in Reference 2); however, there has always been a concern that military crashworthiness design criteria are not directly applicable to the civil fleet. It has been argued that the aircraft types, uses, and crash environments are significantly different. The previous study sponsored by the FAA Technical Center (Reference 1) supported this position by conclusively demonstrating that the crash environments of U.S. civil and military helicopters are indeed significantly different. If the military crash resistance design criteria (described in Reference 2) were applied to the civil fleet, a severe weight and cost penalty would be imposed on civil helicopters. Further, the rationale for providing crash resistance is significantly different between civil and military rotorcraft. The FAA's goal is to specify minimum acceptable safety criteria for manufacturers and users. However, the military is the ultimate user and can justify high levels of crashworthiness due to the payback in terms of combat readiness.

Identifying levels of crash resistance that could realistically be incorporated into future civil rotorcraft without excessive weight and cost penalties was the primary focus of this effort. The approach taken in the study consisted of the following five tasks:

1. Identify important design parameters, such as crash environment, crash impact parameters, and energy absorption structural characteristics.

2. Review existing design and analysis techniques for crash-resistant landing gear, fuselage structures, seats, and fuel systems.

3. Prepare conceptual designs for crash-resistant systems that could be incorporated into rotorcraft representative of the civil fleet. Consider various levels of crash protection in the completed designs.

4. Conduct a trade-off study to obtain the optimum crash resistance level for civil rotorcraft considering the expected crash environment.

5. Define design and test criteria for future civil rotorcraft.

The remainder of this report describes the results of these five tasks.

2.0 CRASH RESISTANCE DESIGN PARAMETERS FOR U.S. CIVIL ROTORCRAFT

This section discusses the development of crash resistance design parameters based on the latest results from various research and development studies. The crash environment and important crash impact conditions associated with this crash environment were quantified from accident data. Structural characteristics typically found in civil rotorcraft were also considered in development of appropriate design parameters.

2.1 ROTORCRAFT CRASH ENVIRONMENT

The results of published analyses of the crash environments for U.S. civil, U.S. Army, and U.S. Navy helicopter accidents (References 1, 2, and 3) were used as a basis for this evaluation. It is helpful to compare data on the civil rotorcraft crash environment to the military crash environment since the latter data have been used to formulate extensive design and test criteria for military aircraft. Figure 1 presents the important crash impact parameters that define the crash environment:

- Impact surface
- Impact velocity vector
- Aircraft attitude at impact.

A comparison of the types of impact surfaces associated with survivable civil and military helicopter accidents is given in Table 1. For all categories, the highest percenta ge of accidents occur on soft ground. The Army accidents have a higher frequency of occurrence of impacts in trees and vegetation, while the Navy accidents have a higher occurrence of impacts in water. Civil accidents, unlike Army or Navy accidents, have a higher frequency of occurrence on prepared surfaces. This distinction is critical because it influences the selection of crash-resistant systems to provide improved protection (e.g., crash-resistant landing gear can be highly effective when impacting on prepared surfaces).

Table 1.
Types of impact surface for survivable U.S. civil and U.S. military accidents

Terrain Type	Frequency (%)		
	Civil	Army	Navy
Soft ground (soft, sandy, plowed)	40	49	44
Vegetation (trees, large shrubs)	16	30	8
Uneven ground (rocks, stumps, logs)	9	10	3
Prepared surface (paved, hard dirt, gravel)	18	7	0
Water	11	2	39
Snow/frozen	6	2	3
Other	0	0	3

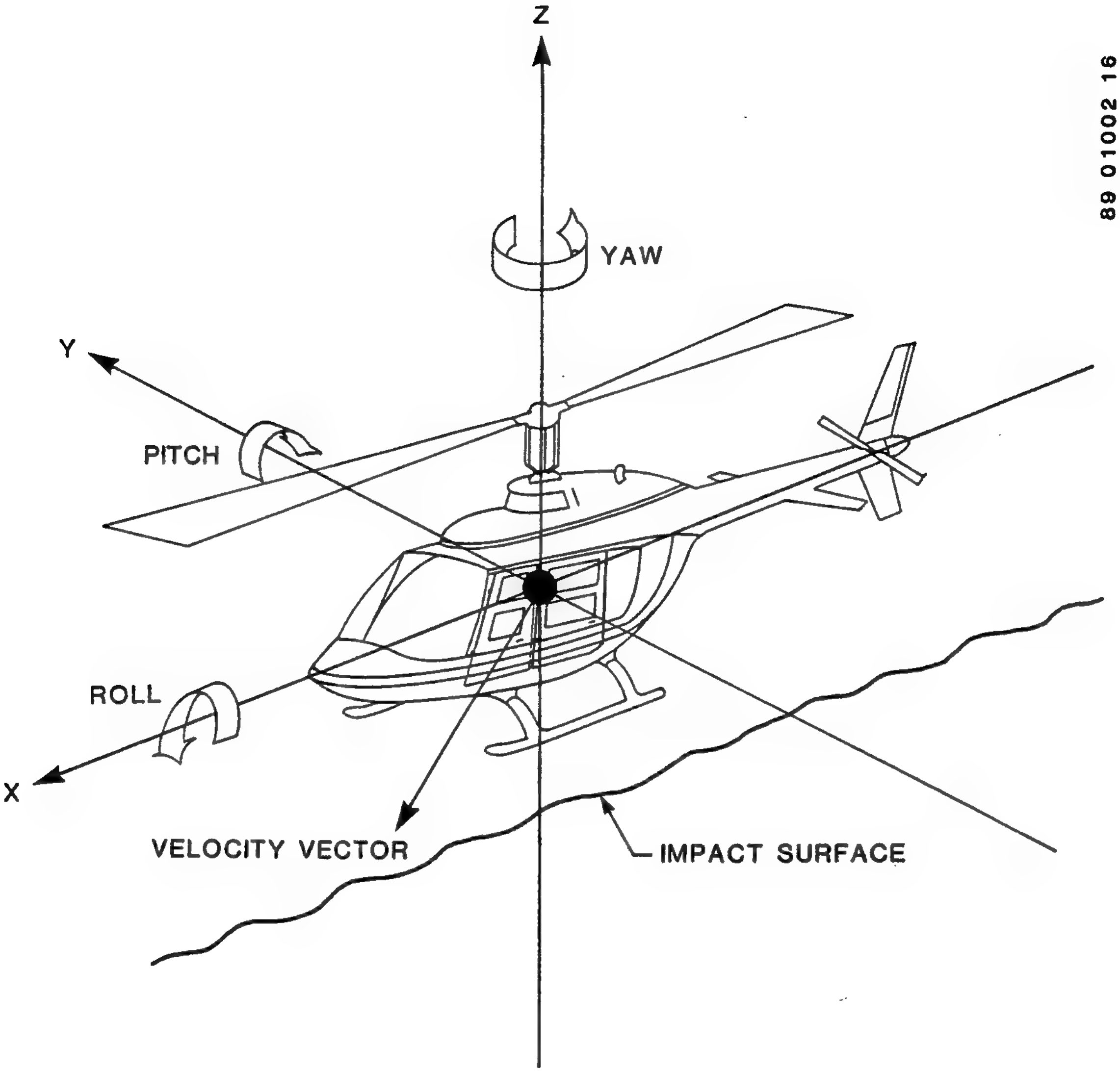


Figure 1.
Crash impact parameters.

The vertical impact velocity change distribution for civil, Army, and Navy helicopter accidents is shown in Figure 2. The vertical velocity change distributions for the three user groups are quite different. For example, the Army vertical velocity change for the 95th-percentile survivable accident is 42 ft/sec compared to 26 ft/sec for civil helicopters. Since the associated kinetic energy is a function of the velocity squared, the Army vertical velocity results in approximately 2.6 times more impact energy than the 95th-percentile survivable civil helicopter accident. However, comparisons of the longitudinal impact velocity change distributions for both civil and military helicopter accidents presented in Reference 1 show a close correlation.

The roll, pitch, and yaw attitudes at impact for civil survivable helicopter accidents are shown in Figure 3. The data in Figure 3 indicate that a high percentage of the accidents tend to fall within the $\pm$10-degree roll and +5/-15-degree pitch attitudes. The distribution of roll and pitch attitude for Army helicopter accidents (Reference 2) tends to be similar to that of civil accidents.

2.2 CRASH IMPACT PARAMETERS

From a review of both civil and military airframe structure design criteria (Reference 4), it was found that the most comprehensive criteria were contained in the U.S. Army's Aircraft Crash Survival Design Guide (Reference 2) and MIL-STD-1290 (Reference 5). A comparison of the types of criteria currently used by the U.S. military and the FAA is summarized in Table 2. Civil rotorcraft design criteria were identified in Reference 1 and were based on providing occupant protection for crash impacts up to and including the level of severity of the civil 95th-percentile survivable accident. The design conditions for vertical, longitudinal, and lateral impacts of these civil rotorcraft are shown in Table 3 and are summarized below.

1. Vertical impacts are most severe on hard surfaces where there is no energy absorption provided by ground deformation. Energy absorption capability for vertical impact may be incorporated into the landing gear, fuselage, and seats. A typical crash pulse in the vertical impact direction is shown as Condition No. 2 in Table 3. This impact condition defines the need for energy absorption capability in the landing gear, fuselage, and seats. Soft surfaces can provide additional energy absorption capability for vertical impacts by ground compaction, although landing gear may not function effectively under these conditions.

2. Longitudinal impacts tend to be most severe on soft soil when plowing is likely to occur. A typical crash pulse in the longitudinal impact direction is shown as Condition No. 1 in Table 3. Unlike the vertical impact, much of the impact kinetic energy can be absorbed after the initial impact through friction as the aircraft slides to a stop. Airplane crash tests by the National Aeronautics and Space Administration (NASA) (Reference 6) show dramatic differences in accelerations and structural damage for comparable longitudinal impacts onto a rigid surface (relatively mild impact) and onto soft soil (very severe impact). Design for longitudinal impact on soft soil involves designing the forward underfloor to be strong and sled-like to resist plowing. Adequate tiedown strength for the seats and large overhead masses must be provided. In addition, frontal impact into an obstruction, Condition No. 4 in Table 3, should also be considered.

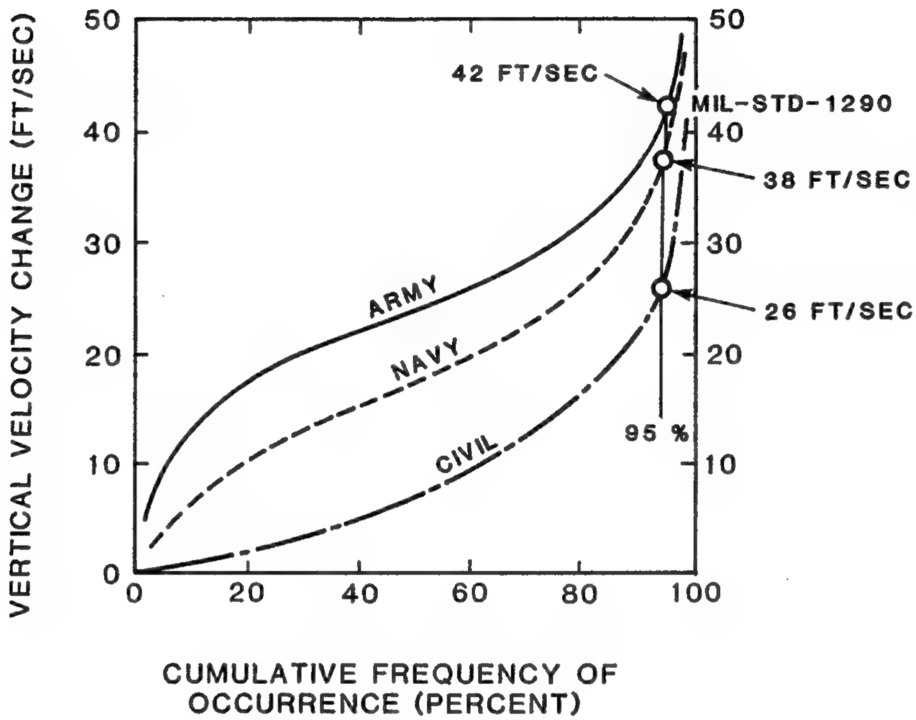


Figure 2.
Vertical velocity changes for U.S. military and U.S. civil survivable rotorcraft accidents.

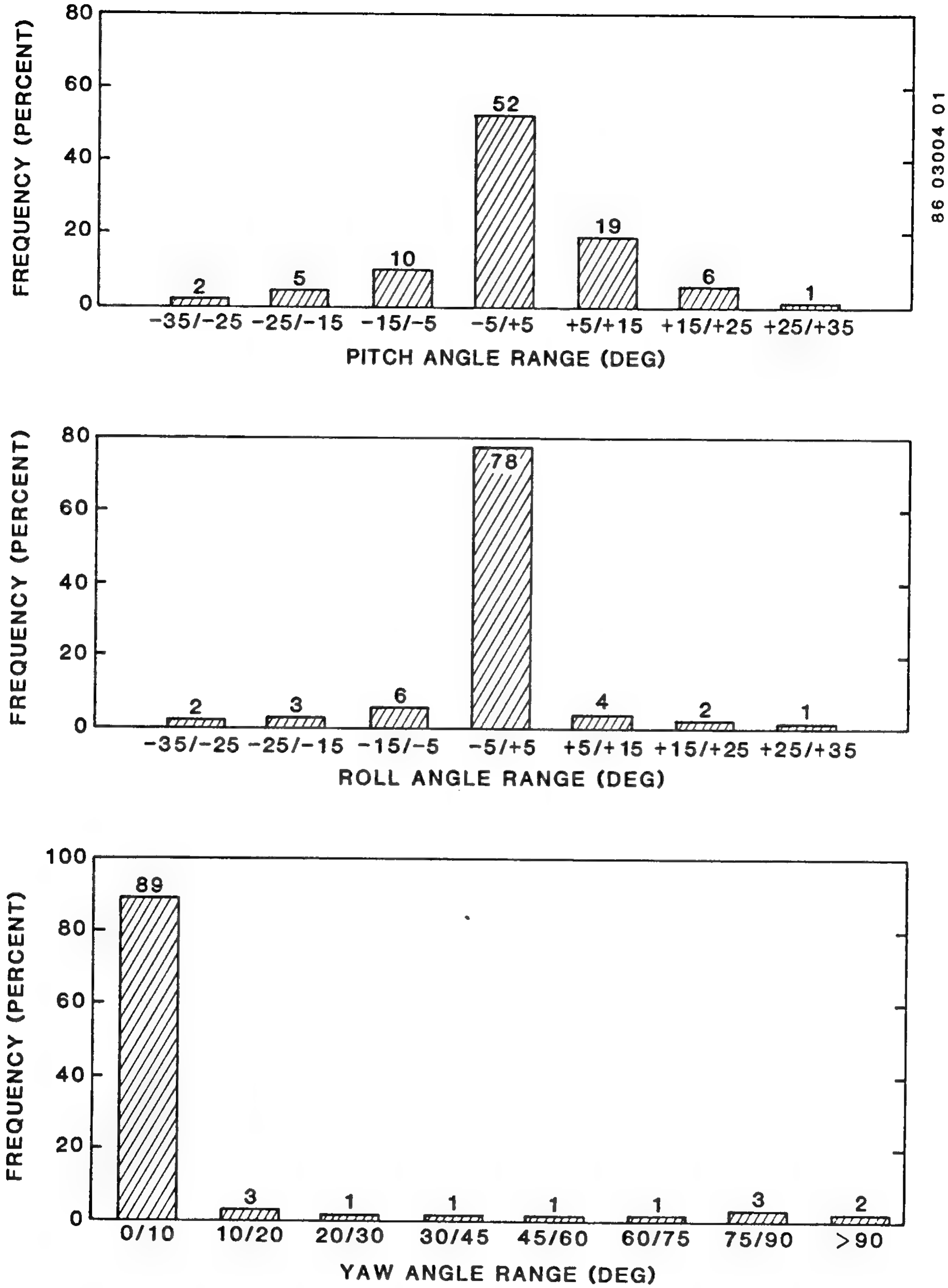


Figure 3.
Impact attitudes for U.S. civil accidents (from Reference 1).

Table 2.
Current airframe structure crash resistance design criteria

Airframe Crash Resistance Consideration	Army (MIL-STD-1290 and TR-79-22)	Navy (AR-56)	Air Force (MIL-A-8860 and MIL-A-8865)	(FAR 23, 25, 27, and 29)
Airframe Protective Shell	x	x		
Breakaway Airframe Structure	x			
Occupant Strike Hazard	x			x
Energy Absorption	x			x*
Postcrash Hazards	x			x
Failure Modes	x			
Inertial Forces	x	x	x	x

*For seats and landing gear only.

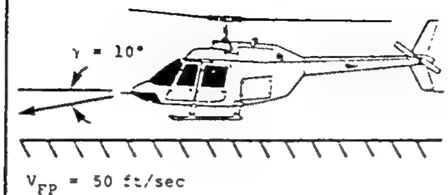
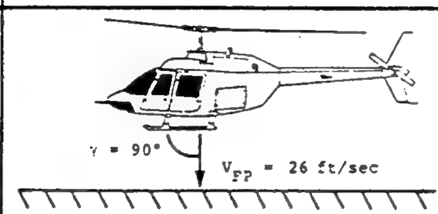
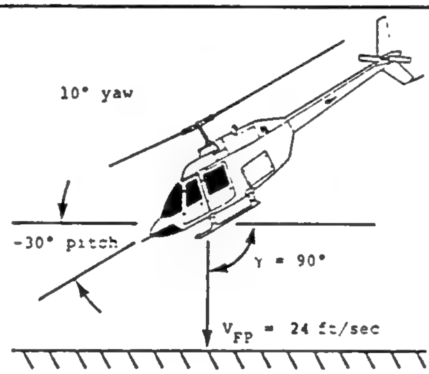
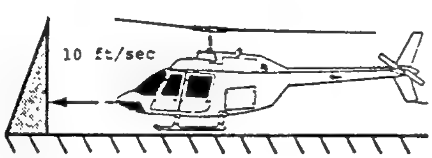
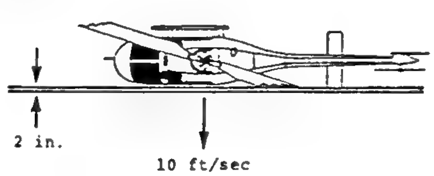
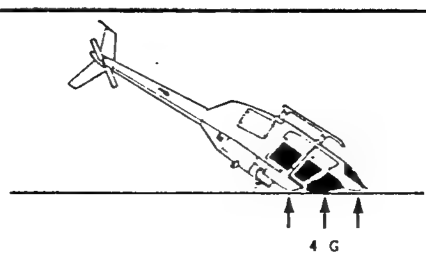
3. Lateral impact velocities are generally quite low compared to vertical and longitudinal velocities and may be the result of rolled or yawed impact conditions, or from rollover following the principal impact. Lateral impacts may also occur if the helicopter falls through trees and impacts on its side, generally on soil. These types of impacts are shown in Table 3 as Conditions No. 5 and 6.

2.3 CRASH RESISTANCE DESIGN CONSIDERATIONS

Design of an aircraft for crash impact should involve a systems approach utilizing landing gear, fuselage structure, and seats to absorb aircraft kinetic energy and minimize impact loads on the occupants (Figure 4). In addition, the occupants must be properly restrained and a protective shell maintained around the occupied areas to provide a livable volume during a crash. Postcrash hazards, such as fire, must also be considered in an effective crash-resistant design. All critical components must be integrated as a system using prudent design requirements that avoid any "weak links" if underdesigned, or an excessive weight penalty if overdesigned.

There are many factors to consider when designing the airframe structure to withstand a crash impact (Figure 5). Of prime importance is to design the airframe to maintain structural integrity and a livable space for the occupants. To accomplish this, the airframe structure should incorporate a high-strength protective shell or cage around the occupants. The structure should provide rollover strength and a strong support structure to restrain large-mass items and seats. It should also maintain the integrity of exits for emergency egress. Furthermore, the forward

Table 3.
Recommended airframe design impact conditions for newly certificated rotorcraft models (Reference 1)

Condition Number	Impact Condition*	Impact Surface	Intent
1		Soft ground	High-speed, run on landing. Major impact deforms/removes gear, damages fuselage under-structure. "Plowing" of fuselage should be prevented.
2		Hard, smooth surface	Pure vertical impact. All energy-absorption capability of gear depleted. In order to minimize hazard to occupants, fuselage understructure and/or seats must attenuate deceleration pulse. Overhead structure and high mass items must stay in place.
3		Hard, smooth surface	Combined - axis impact. Landing gear probably will not function. Forward portion of fuselage takes brunt of impact. Intrusion into livable volume of the cockpit should be minimized. Tests multi-axis retention capability of major components.
4		Rigid obstacle	Sliding aircraft encounters rigid obstacle. Airframe must be strong enough to prevent structural deformation that impinges on occupants. Less than 15 percent reduction in cockpit volume is desirable.
5		Soil or water. Aircraft buried 2 in.	Impact in 90-degree roll attitude to either side. Contact forces distributed over buried airframe surface. Internal volume should not be reduced by more than 15 percent.
6		Soil. Aircraft buried 2 in.	Frontal plane of cockpit impacts ground as aircraft flips end over end. 4-G load distributed over airframe structure (not canopy) buried in ground. Intrusion into livable volume of cockpit should be minimized.

*γ = flight path angle.

V_{FP} = Flight Path Velocity.

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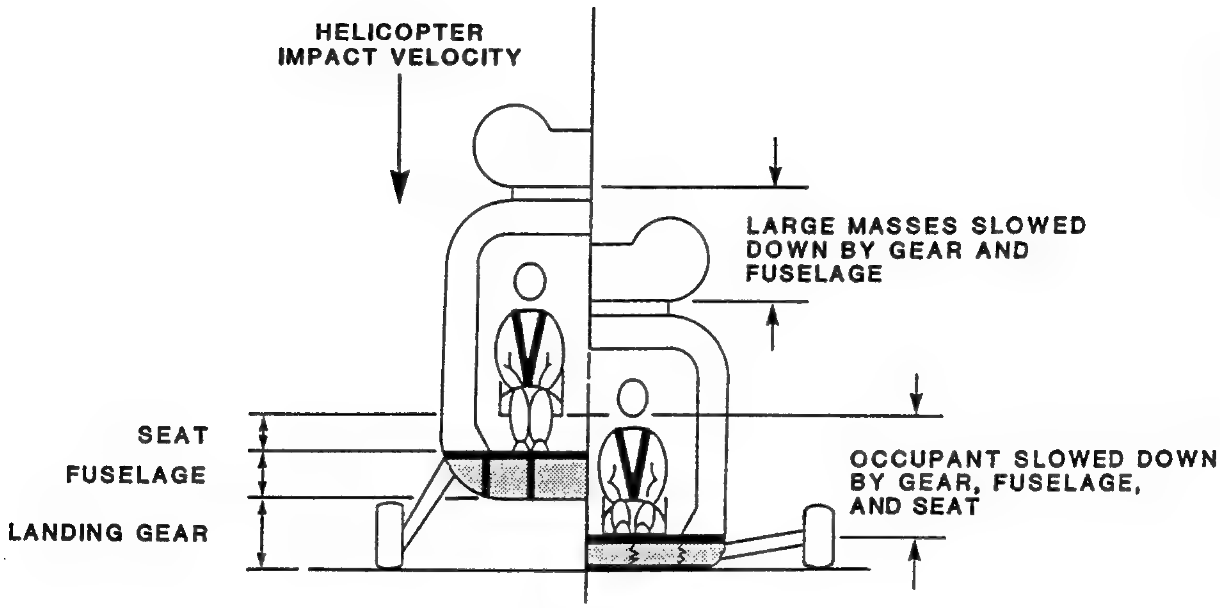

Figure 4.
Energy management system.

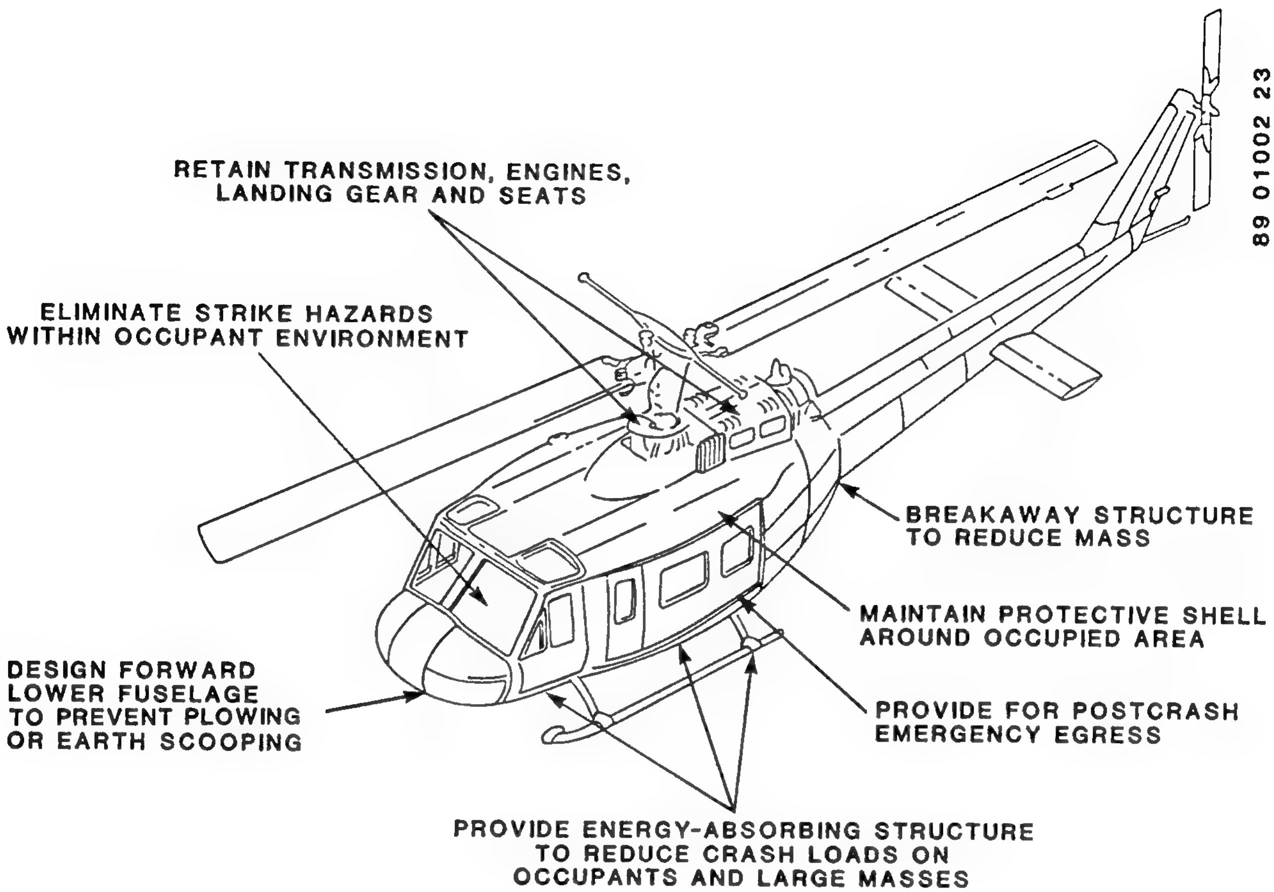

Figure 5.
Airframe structure crash resistance design features.

fuselage structure should be designed to minimize plowing and to absorb energy during longitudinal impacts into obstructions. Underfloor crushable structure should be capable of absorbing energy in a vertical crash impact. This crushable structure should be designed to carry normal airframe loads as well as to absorb a significant portion of crash energy; otherwise, an excessive weight penalty will be paid. Structure that supports the seats must maintain adequate strength throughout the crash. If the seat support structure is allowed to crush it must maintain enough structural capability to support the seat loads. If the seats are energy absorbing, the crushing structure must not interfere with the stroking seats.

The final consideration in aircraft crash-resistant design is the need to minimize postcrash hazards, of which fire is the most significant in land impacts. The fuel system should be designed to minimize fuel spillage from the fuel tanks or bladders, and from fuel lines throughout the fuselage. This is a difficult task due to the extensive damage that can occur in a crash. Additionally, emergency egress is a critical consideration in water impacts because occupants may be disoriented and the helicopter may sink. Even the best design for egress can be neutralized by the occupants' disorientation.

2.4 ENERGY ABSORPTION STRUCTURAL CHARACTERISTICS

Several elements of the airframe structure contribute to the overall energy absorption capability of the helicopter. The fuselage should be designed to maintain a protective shell around the occupants while it acts in combination with the landing gear and seats to absorb the impact kinetic energy. The energy-absorbing, load-attenuating subfloor structure in the fuselage reduces the magnitude of inertial forces transmitted to the occupants and the large-mass items, such as the transmission and engine. The load-attentuating subfloor also helps maintain the protective shell by reducing and distributing transmitted loads. There are an infinite number of design combinations for proportioning the relative amounts of energy absorption in each of the fuselage elements. However, the manner in which the energy absorption capability is distributed can significantly effect the overall efficiency of the fuselage design. Energy absorption trade-offs are needed early in the design of a new aircraft to determine the optimal distribution of energy absorption in the fuselage elements to meet weight and cost goals.

The energy-absorbing structure consists of a crush zone incorporated into the floor that provides energy absorption and load attenuation. It is also important that the energy-absorbing structure be dual purpose; that is, it must serve as a load-carrying structure under normal operation and provide energy absorption in a crash. This will result in a lightweight structural design.

Several important characteristics must be considered when evaluating and selecting energy-absorbing devices for potential application to the airframe structure, including the following:

Energy absorption efficiency - The crushing load-stroke response curve should be rectangular in shape to provide maximum energy absorption.

Energy dissipation - The energy-absorbing structure should not store the crash energy or excessive rebound will result.

Specific energy absorption (SEA) - SEA is the ratio of energy per unit weight. Ideally, the SEA should be as high as possible.

Stroke-to-length ratio - This should be as high as possible to obtain maximum usable stroke with the limited depth of structure under the helicopter floor.

Combined loading capability - The subfloor structure may be subjected to longitudinal, vertical, and lateral loading, and combinations of these; thus, energy-absorbing devices must function under these conditions.

Load control - The load-deflection curve should not exhibit high peak loads that exceed the supporting frames and floor structure capability.

Rate-of-loading effects - The load-deflection behavior and energy absorption capacity of the energy-absorbing structure should be minimally affected by the rate of loading since this can vary widely with crash conditions.

3.0 CRASH RESISTANCE TECHNOLOGY SURVEY

A literature search and survey of principal helicopter manufacturers was conducted to identify technology appropriate for use in civil rotorcraft. The survey sought information on analytical techniques, design approaches, and applicable materials. The technology described here was developed primarily for use in civil aircraft, or could be adapted to civil aircraft based on its successful use in military aircraft.

3.1 ANALYTICAL METHODS

A key to being able to evaluate and optimize the crash tolerance of helicopters is the establishment of comprehensive analytical tools that will aid the aircraft designer. Designing a crash-resistant structure requires an understanding of its complex behavior as it deforms under crash impact loads. Nonlinear computer techniques are needed to complement the linear elastic (small deflection) finite element design analysis methods (such as NASTRAN, Reference 7) that are presently being used for strength and vibration analysis.

Three analytical methods that have been used for helicopter structural crash simulation are shown in Figure 6 and are described by the following levels of capability:

Basic - The simple capability simulation, such as the CRASH program (Reference 8), can be used to evaluate gross responses or design trends. This type of simulation features large structural assemblies modeled as single crush elements, up to 10 masses and 50 degrees of freedom (unknowns in motion equations), and one- or two-dimensional geometry and motions.

Intermediate - The KRASH program (Reference 9) is an example of an intermediate capability that is a widely used analytical method for helicopter airframe structure. KRASH is a nonlinear transient-response analysis for simulating the crash impact behavior of any arbitrary three-dimensional structure. The analytical capability includes both geometric and material nonlinear structure behavior. KRASH is often referred to as a "hybrid" crash analysis method because it generally requires input data derived from tests. The structure is represented in a rather coarse manner using nonlinear beam and spring structural elements and lumped masses.

Detailed - The DYCAST program (Reference 10) is an example of a detailed capability simulation and has been applied to helicopter structures (References 4 and 11). DYCAST is a finite-element code with the capability of modeling stringers, beams, and structural surfaces, such as skins and bulkheads. Some of the major DYCAST features important to the engineer are nonlinear (spring, stringer, beam, and orthotropic thin sheet) elements, plasticity, very large deformations, variable problem size, restart, deletion of failed members, variety of numerical solution methods, and modular formulation.

The KRASH computer program is the most widely used analytical technique for impact modeling. It has been used to simulate the impact of the U.S. Army's YAH-63 helicopter, a major structural component such as the composite cabin section of a helicopter, and the configuration of an advanced landing gear. A discussion of these examples and how they pertain to the design of a crash-resistant fuselage and landing gear follows in the next three sections.

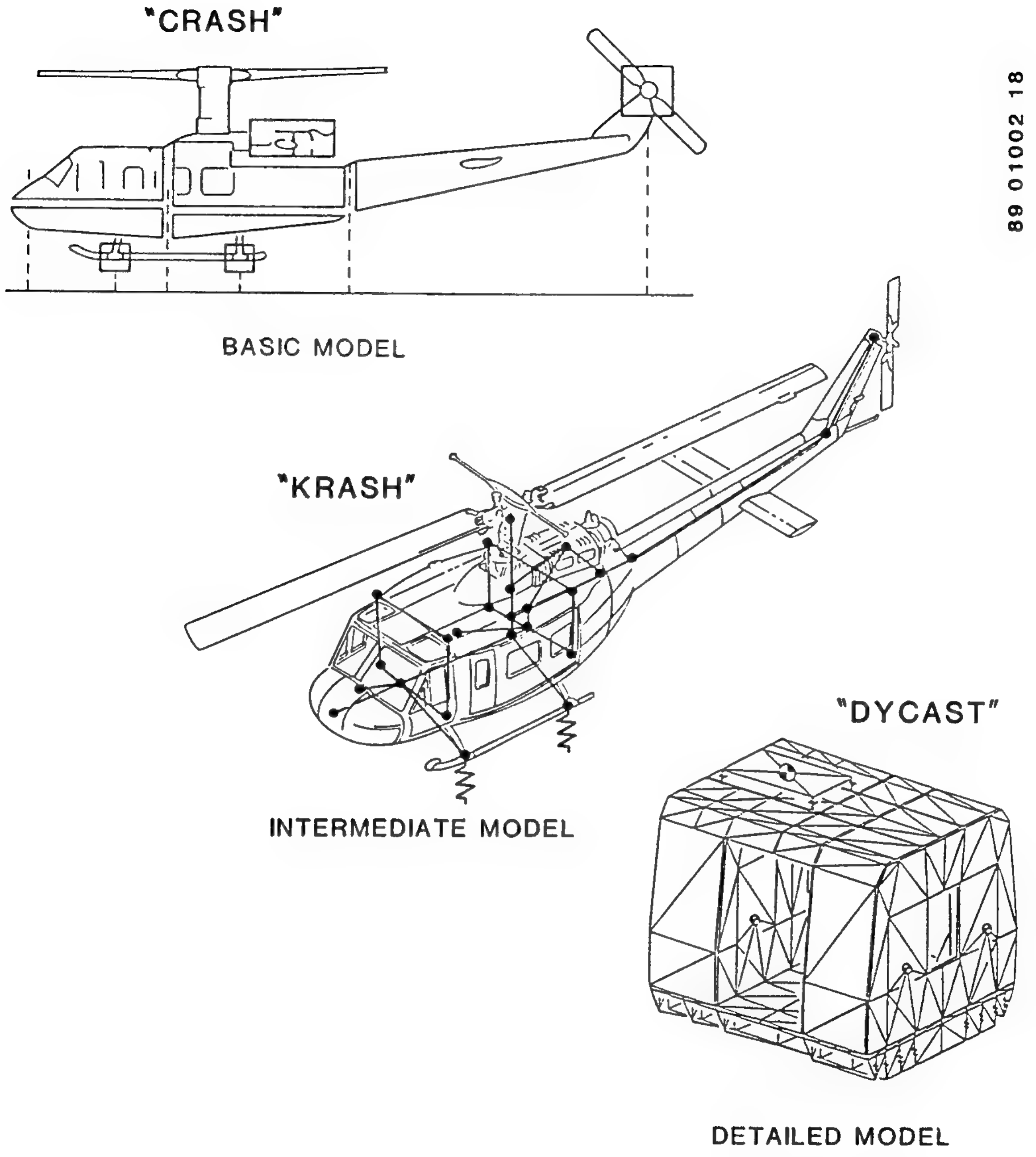

Figure 6.
Crash simulation capability levels.

3.1.1 Full-Scale YAH-63 Helicopter

In July 1981, the U.S. Army conducted a full-scale drop test of the YAH-63 prototype helicopter at the NASA Langley Impact Dynamics Research Facility (Reference 12). The YAH-63 was designed to the Army's crashworthiness requirements contained in MIL-STD-1290, including a 42 ft/sec vertical impact condition. The YAH-63 helicopter incorporated many crash resistance features, including high-energy landing gear, crushable fuselage structure, energy-absorbing seats, high strength retention of large masses and seats, and a CRFS. The primary objective of the drop test was to evaluate performance of crash resistance features of the YAH-63 under crash impact conditions representative of a Army 95th-percentile potentially survivable accident. A KRASH simulation of the YAH-63 crash test was conducted for validation of this analytical tool as a method for design of airframe structures for crash impact (Reference 13).

A comparison of the KRASH simulation results with the full-scale drop test, at comparable time intervals, is shown in Figure 7. The comparison of the KRASH results with the drop test showed good agreement for landing gear energy absorption, fuselage crushing, nose structure failure, and copilot/gunner seat stroking. The acceleration levels of the large masses (transmission and engines) in the mid-fuselage also agreed well with the test data. The general agreement of the important structural responses between KRASH and the drop test indicates that the analysis can be a useful design tool provided the critical structural elements (landing gear energy absorption, fuselage crushing and dynamic response, structure failure modes, and seat stroking) are properly represented.

3.1.2 Composite Structural Component

Two full-scale composite cabin sections were designed, fabricated, and crash tested under an FAA/Army-sponsored research and development (R&D) program. The drop test conditions for the two cabin sections were representative of the 42 ft/sec vertical crash impact velocity requirement specified in MIL-STD-1290. These test conditions assume the landing gear had slowed the aircraft from 42 ft/sec to 30 ft/sec prior to fuselage contact. Roll attitudes of 0 degrees (flat) and 20 degrees were used in the two cabin drop tests. The results from both drop tests indicated that the strong protective shell structure around the occupants remained intact; structural deformation was restricted to the areas designed to crush and absorb energy. And most important, the excellent posttest condition of the cabin protective shell structure and the performance of specially designed energy-absorbing components demonstrated the crash impact capability of the composite structure (Reference 11).

For design of the composite cabin sections, programs KRASH and NASTRAN were used in conjunction with each other. KRASH was used for the crash impact analysis of the composite cabin drop test conditions and NASTRAN was used for determining internal loads required for strength analysis. The KRASH model of the cabin test section is shown in Figure 8. Load deformation characteristics of key energy-absorbing components were derived from design support test data and used as input to the KRASH analysis. The NASTRAN analysis was conducted using applied load factors from KRASH based on a "snapshot" of the dynamic loads at points in time when the loads were critical. For the NASTRAN analysis, the structure was assumed to remain elastic. This was considered a reasonable assumption since all of the primary structure above the floor was designed so that it would not sustain yield damage under the specified crash conditions. In the primary protective shell structure, any yielding was considered unacceptable because of the characteristic brittle failure modes of composite materials.

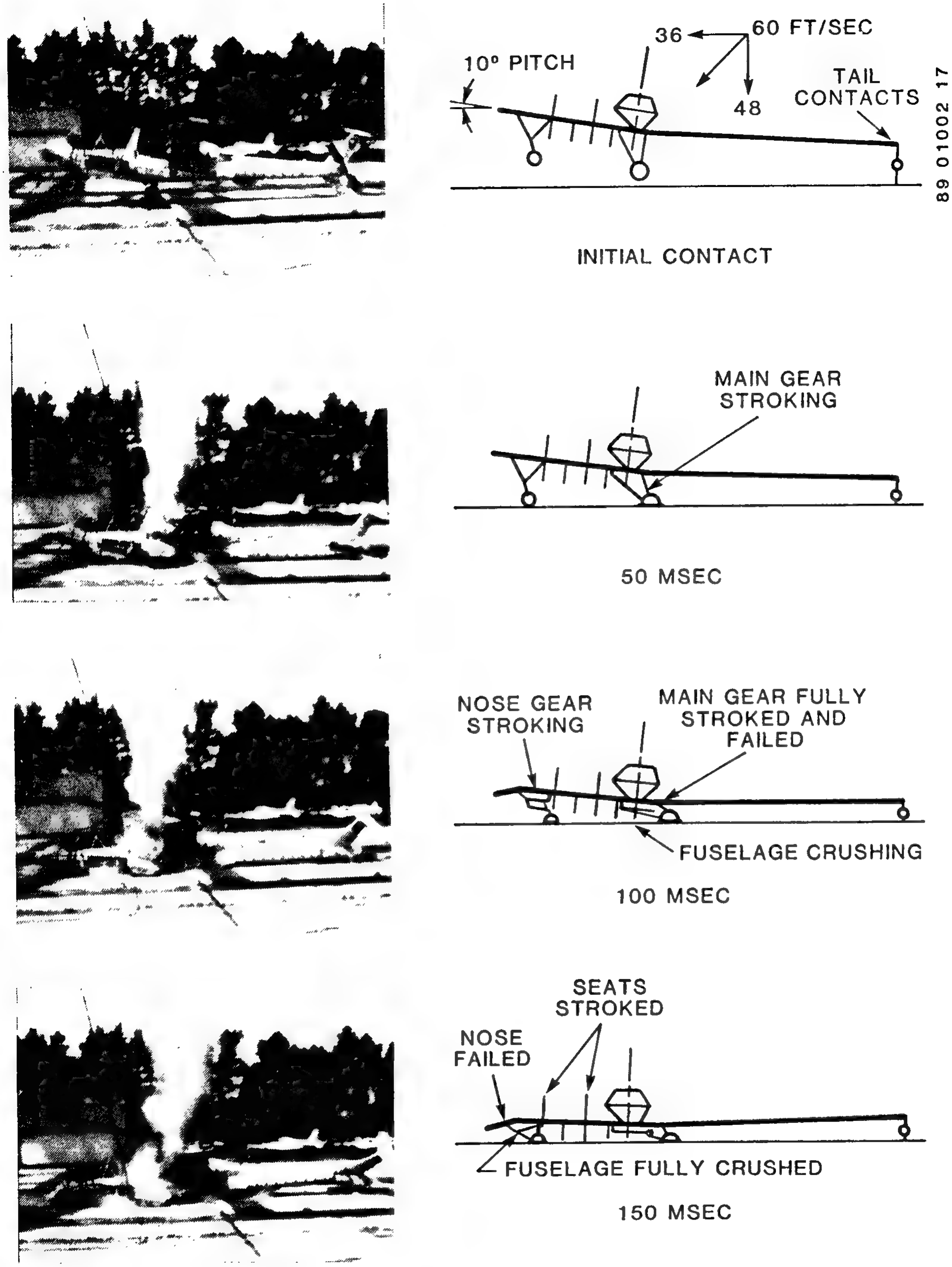

Figure 7.
Comparison of YAH-63 drop test and KRASH simulation.

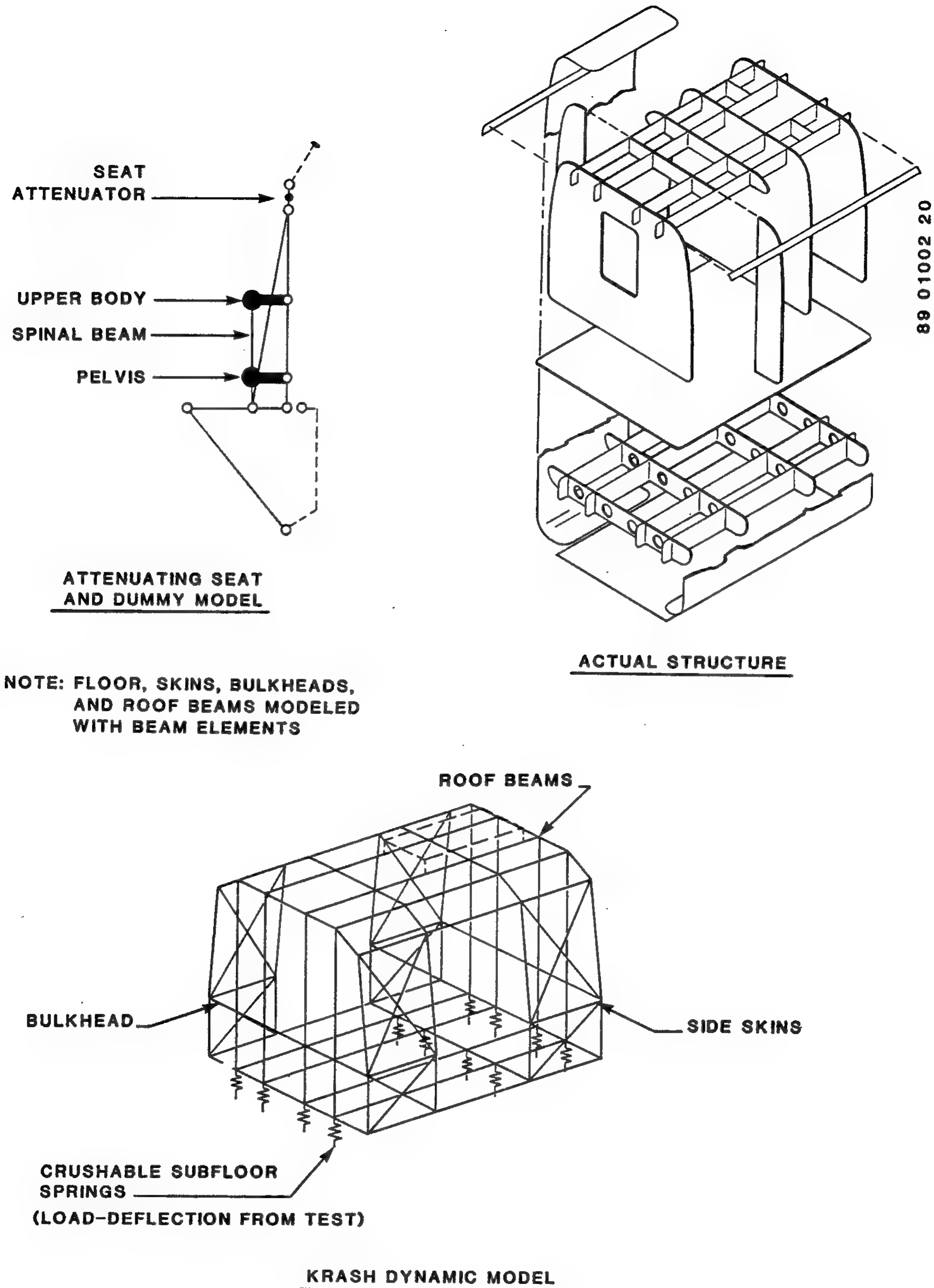

Figure 8.
KRASH mathematical model of composite cabin section.

Based on the successful crash impact performance of the composite cabins and the comparison of analytical and test results (see Reference 11), KRASH proved to be a useful and reasonably accurate tool for the design of helicopter composite structures for crash impact.

3.1.3 Landing Gear Performance

The traditional method of validating landing gear performance has been a series of trial drop tests. This approach is becoming less feasible as crash resistance requirements extend the conditions under which these gear must perform. Sikorsky Aircraft conducted a program to validate program KRASH for prediction of landing gear performance (Reference 14). The goal of the research study was to verify that KRASH could model a range of landing gear types and impact conditions, thereby reducing the amount of testing for future landing gear development programs.

Sikorsky used the KRASH-85 version of the computer program to simulate dynamic performance of three types of landing gears for comparison to actual drop test results. The three types of landing gear considered in the study included:

- A retractable, conventional oleo landing gear with 8-ft/sec capability
- A crash-resistant, swinging arm gear with dual oleo shock strut with 34.5-ft/sec capability
- An articulating gear with both an oleo and a crushable honeycomb shock strut with 20-ft/sec capability.

Figure 9 shows a schematic diagram of each of the three landing gear designs and the representative KRASH model.

The three KRASH landing gear models were found to provide good correlation between predicted and actual measurements of ground loads, drop mass displacements, and velocities. A further benefit of the KRASH analysis was the prediction of dynamic loading in structural members of the landing gear. The dynamic loading data would allow more accurate stress analysis and optimization of the design.

3.2 FUSELAGE STRUCTURES TECHNOLOGY

A literature survey was conducted to gather information about existing fuselage and landing gear concepts which show promise in providing energy absorption and in controlling the loads transmitted to the occupiable volume of an aircraft during impact. Particular attention was focused on concepts applicable to civilian rotorcraft.

The Bell Helicopter Textron Inc. (BHTI) computer library was used to conduct a multilevel search of several databases to locate applicable references. The abstracts were reviewed for information relative to crash resistance design principles in light aircraft. A significant amount of information has been generated in recent years on the compressive response of both metal and composite materials in static and dynamic environments. A summary of the relevant research is presented in the following sections.

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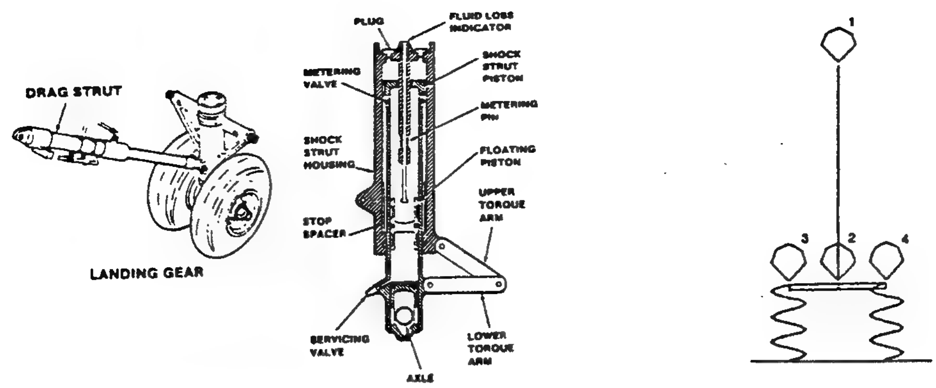
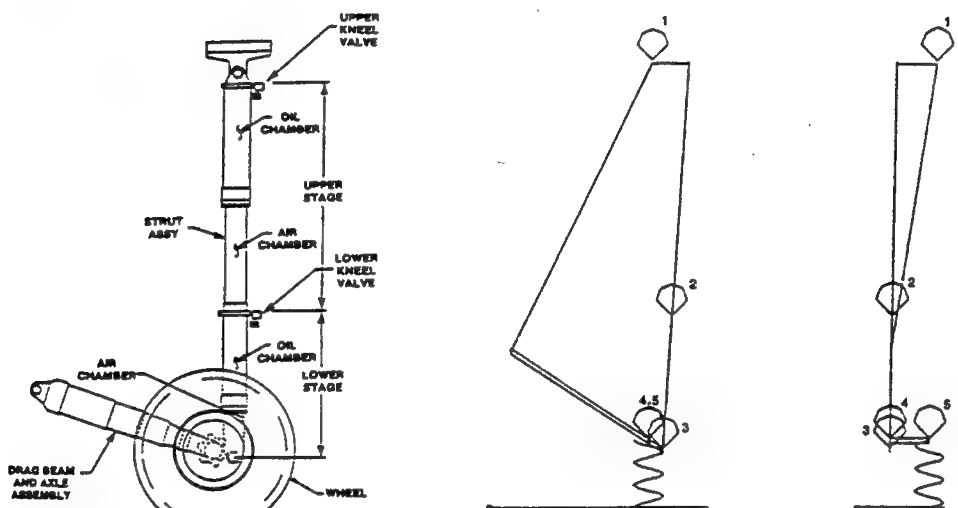
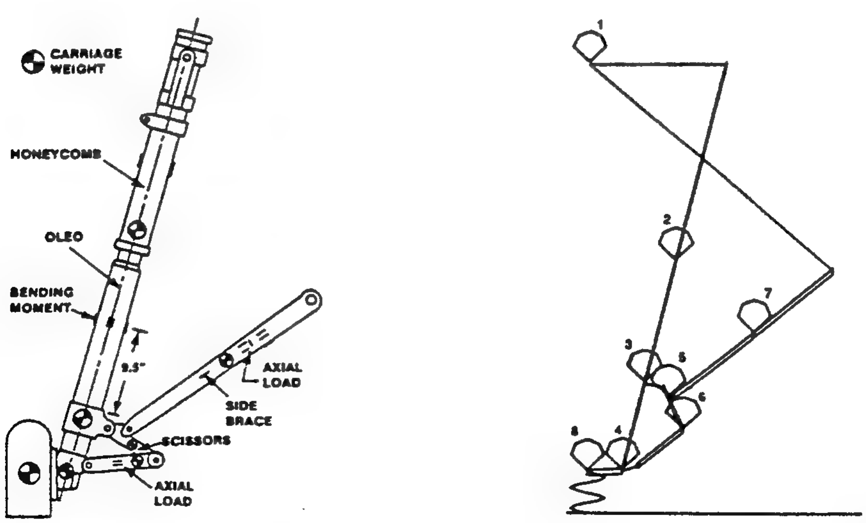


(a) Retractable, conventional oleo gear and KRASH model (front view)



(b) Swinging arm gear with dual oleo strut and KRASH model



(c) Articulating gear with oleo and crushable honeycomb, and KRASH model

Figure 9.
Three landing gear configurations and KRASH models (from Reference 14).

3.2.1 Materials Analysis

Extensive research has been conducted on the inherent energy absorption properties of structural materials. These studies can be divided into two groups: those that concentrate on the mechanical properties of the materials and those that examine the properties of these materials fabricated into basic structural building blocks. Some of the representative studies are summarized below.

The Southwest Research Institute performed a study for the U.S. Navy which investigated the use of various honeycomb and foam materials for energy absorption, large mass retention, and padding (Reference 15). A study of the merits of composite sandwich construction over monocoques or semi-monocoque construction was performed by Jahnle (Reference 16) and Raschbichler (Reference 17) for the automobile industry. The lower longitudinal frames and bumpers of an automobile were replaced with sandwich panels and tubes constructed of a polyurethane foam core and fiberglass sheets. The result was that the sandwich design was superior in energy management, compared to monocoque construction. Another investigation of composite sandwich construction was conducted by Foye and Hodges (Reference 18). One conclusion they made was that sandwich construction absorbs more energy than a stiffened skin construction, which is a common design of standard aerospace fuselage underfloors.

Ezra and Fay (Reference 19) performed a study in 1972 on the energy absorption capabilities of various mechanisms using composite concepts. This study was intended to identify energy absorption mechanisms for use in aircraft impact. A joint NASA/Army research program conducted by Farley has provided a significant data base of comparative studies for micro-mechanical behavior of composite and hybrid materials under representative crash conditions (References 20 through 27). Some of the areas investigated were fiber volume fraction, stacking sequence, geometry/stability, fiber matrix failure strain allowables, fiber stiffness, ply orientation, hybridization, and stitching.

Kindervater also conducted tests of various elemental shapes fabricated from composite materials for determination of their energy absorption capabilities (Reference 28). These shapes included stringer stiffened, sandwich, and integrally stiffened beams. The parameters of interest in these static and dynamic tests were failure modes, SEA, crush load uniformity, impact effects, and failure trigger mechanisms. The composites outperformed the aluminum specimens, and the integrally stiffened beam concept provided the best energy absorption.

3.2.2 Crash-Resistant Structural Components

The goal of the materials research was to provide a basis for developing more complex structural assemblies designed to absorb crash energy. A large body of work exists that examines structural energy-absorbing components for various types of aircraft. One pioneering study on aircraft crash dynamics for general aviation aircraft was performed by engineers at NASA Langley Research Center and BHTI (References 29 and 30). This five-year program identified the crush behavior and important design parameters for metal underfloor structures designed with application to a future full-scale test program. This research program led to 32 full-scale crash tests of standard and crash-resistant underfloor structures (Reference 31) which provided a significant data base for the development of crash resistance analysis capabilities for light aircraft.

NASA continued its development of energy-absorbing structural design concepts for composites in much the same fashion as it did for the metal program. The initial material and element level testing was the starting point, as discussed above, and the program was structured to progress through the subassembly testing and full-scale testing stages (Reference 32).

As previously mentioned, BHTI conducted an investigation of energy-absorbing composite structural design under a U.S. Army and FAA-sponsored development program. Under this program, a full-scale composite cabin section was drop tested (Reference 11). The cabin section incorporated a Kevlar®/epoxy sandwich crushable underfloor. This design concept was also used on the composite airframe developed under the Army-sponsored Advanced Composites Airframe Program (ACAP). BHTI found in these studies that the initiation of crushing, off-axis stability, and postcrash integrity were very sensitive to the subfloor design parameters.

Hughes Helicopter (now McDonnell Douglas Helicopter Company) investigated a composite skin-stringer concept using 25-in. subassemblies to validate its crash resistance (Reference 33). The skin-stringer design, which does not use any honeycomb or sandwich construction, achieved a 25 percent reduction in weight over the existing production structure and met the 42 ft/sec Army design criteria specified in MIL-STD-1290.

Mens (Reference 34) reported research and development work on Aerospatiale's concepts for metal crash-resistant structures. In addition to crushable stiffened skin underfloor concepts, Aerospatiale's approach used deformable structural frames which provide retention strength and energy absorption for large overhead masses.

A recent study performed by Simula Inc. under Army funding examined concepts for fiber-reinforced thermoplastic matrix composite materials for use in energy-absorbing subfloor structures (Reference 35). This work continued that conducted previously by BHTI for composite subfloor structures. However, the thermoplastic matrix composites offer a number of potential advantages over previously examined thermoset matrix composites. The primary advantage is the rapid processing cycle for these materials that could result in substantially reduced costs for energy-absorbing subfloors.

3.3 LANDING GEAR TECHNOLOGY

A survey of current landing gear technology identified few studies in which technology appropriate for civil rotorcraft was developed. In contrast, there has been extensive landing gear research for military helicopters sponsored by the U.S. Department of Defense and helicopter manufacturers. However, the design criteria and performance goals differ significantly between military and civil helicopters.

Landing gear for a U.S. Army helicopter designed to meet MIL-STD-1290 criteria are subject to a wide range of design requirements. The gear must sustain normal and hard landing loads, absorb large amounts of crash energy, accommodate off-axis crash impacts, prevent roll-over at angles up to 30 degrees, provide a kneeling capability, and, in some cases, retract to reduce drag and radar cross section. Landing gear in a crash-resistant military aircraft provides protection to the fuselage in a hard landing and contributes to the overall energy absorption system for the occupant in a crash.

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The fuselage protection requirement is the major influence on the design of a landing gear for military helicopters. Conversely, this is not a significant design requirement for civil landing gear. Military landing gear must sustain a 20 ft/sec impact without fuselage contact (per MIL-STD-1290), whereas civil rotorcraft must currently comply with a 10.23-ft/sec reserve energy requirement per FAR Part 27 and 8.02-ft/sec per FAR Part 29. The difference in energy absorption capability is significant: The military gear must absorb approximately four times as much energy as a typical civil helicopter landing gear.

A comparison of landing gear weights for civil and military requirements is shown in Table 4 (from Reference 36). These data indicate that a skid gear designed to current FAR Part 29 requirements would weigh approximately 119 lb for an 8,500 lb design gross weight (DGW) helicopter. In comparison, landing gear designed for the same aircraft to meet MIL-STD-1290 requirements would weigh between 300 and 440 lb depending on type. The BHTI study did provide a comprehensive review of guidelines available at the time for landing gear design. These guidelines encompassed design, testing, and analysis capabilities for landing and crash conditions. Army accident data were used as the basis for most of the guidelines. The report investigated the practicality of two current landing gear configurations, one tricycle and one skid gear, for meeting military crash resistance criteria. The study was performed on a generic rotorcraft and provided some basic considerations required to develop a crash-resistant design.

Table 4.
Summary of uninstalled landing gear weights
for a rotorcraft with 8,500 lb DGW (Reference 36)

Configuration	Forward (each)	Aft (each)	Total	Percent DGW
MIL-STD-1290 criteria				
Tailwheel (30°)	125	80	330	4.13
Tailwheel (25°)	120	60	300	3.75
Nosewheel	103	127	358	4.48
Quadricycle	107	113	440	5.50
Skid with shock struts	84	84	419	5.24
FAR Part 29 criteria				
Tailwheel	74	33	181	2.26
Skid	-	-	119	1.49

In military aircraft that have been designed to meet current crash resistance requirements, the landing gear may absorb as much as 50 percent of the crash energy (Reference 37). The large portion of energy absorption contained in military landing gear is a result of a requirement in MIL-STD-1290 to preclude fuselage contact in a hard landing. The landing gear requirements in FAR Parts 27 and 29 are much less stringent, resulting in a design approach that places a higher percentage of energy absorption in the fuselage. Due to this significant difference in required landing gear performance, there is a divergence in the type of gear used for civil and military rotorcraft. Recent military designs favor tricycle gear with a tailwheel (Reference 36), whereas many civil helicopters use skid gear due to its low cost and simplicity. Table 5 shows a comparison of landing gear configuration for U.S. civil and U.S. military helicopters.

Table 5.
Comparison of landing gear configuration for
U.S. civil fleet and U.S. military rotorcraft

Helicopter Type	Manufacturer	Gross Weight (lb)	Tricycle		Skid	Quad-ricycle
			Nose-wheel	Tail-Wheel		
U.S. civil fleet						
B-2	Brantly	1,670			x	
280, F-28	Enstrom	2,600			x	
300	Hughes	2,050			x	
47	BHTI	2,000-2,950			x	
315	Aerospatiale	4,300			x	
316	Aerospatiale	4,850			x	
341	Aerospatiale	3,970			x	
350	Aerospatiale	4,300			x	
206 B	BHTI	3,200			x	
206 L	BHTI	3,900			x	
305	Brantly	2,900			x	
FH1100	Hiller	2,850			x	
500	Hughes	3,000			x	
BO 105	MBB	5,291			x	
S-55	Sikorsky	7,000				x
222	BHTI	8,250	x		x	
205	BHTI	9,500			x	
212	BHTI	11,200			x	
S-76	Sikorsky	11,400	x			
S-58	Sikorsky	13,500		x		
SA 330	Aerospatiale	16,315	x			
214	BHTI	17,500	x			
U.S. military fleet						
OH-6A	Hughes	2,400			x	
OH-58A	BHTI	3,000			x	
UH-1H	BHTI	9,500			x	
AH-1T	BHTI	14,000			x	
SH-2D	Kaman	12,800		x		
AH-64A	Hughes	13,200		x		
UH-60A	Sikorsky	15,850		x		
SH-3D	Sikorsky	20,500		x		
CH-3E	Sikorsky	22,050	x			
CH-46E	Boeing Vertol	23,300	x			
RH-53	Sikorsky	41,126	x			
CH-54A	Sikorsky	42,000	x			
CH-47A	Boeing Vertol	46,000				x

A parametric study of factors influencing landing gear design is presented in Reference 38. In this study, program KRASH was used to evaluate fuselage and occupant response for two landing gear designs undergoing crash loading for a range of impact velocities and angles.

The Army has also sponsored a number of research studies to improve the weight efficiency of landing gear. These studies can be divided into two categories according to their approach to improving weight efficiency. In one set of studies, substitutions of lighter weight materials were used to reduce the overall weight (Reference 39), but the basic design approach was not substantially changed. The second set of studies examined high-efficiency energy-absorbing devices as a method of reducing system weight and/or providing a higher level of crash protection over a range of impact conditions (References 40, 41, and 42).

Studies of landing gear applications for crash resistance also appear in the Army-sponsored ACAP program. The ACAP gear demonstrated sufficient energy absorption to meet the Army's MIL-STD-1290 criteria of 20 ft/sec for the gear alone. Parametric studies were used to investigate the effects of various crash-resistant designs on the overall configuration of the ACAP. A discussion of the performance of the ACAP landing gear designs by BHTI and Sikorsky Aircraft can be found in References 37 and 43.

The literature search identified only three landing gear developmental programs that might have direct application for improving crash resistance of civil rotorcraft. The first study, completed in 1973, examined an improved skid gear for a UH-1 to enhance energy absorption (Reference 44). In this Army-sponsored program conducted by Beta Industries, it was demonstrated analytically that a combined skid and energy-absorbing gear could enhance energy absorption. However, the design concept proved to be ineffective during hardware testing. The second program occurred over a number of years and had the goal of improving the OH-6A landing gear to minimize blade/tailboom strikes in an autorotation landing (References 45, 46, and 47). The technical approach was to interconnect front and rear elements of the gear to minimize pitch velocities by redistributing ground contact forces for nonlevel impacts. The final program of interest involved the actual design of an energy-absorbing landing gear for Aerospatiale's AS332 Super Puma (Reference 48). This aircraft had been developed with both military and civilian applications in mind. The landing gear and heavy box frame structure provide occupant protection up to 33 ft/sec vertical velocity change, which was validated by testing.

3.4 SEATING SYSTEM TECHNOLOGY

Seating system design is one of the most well-developed crash resistance technologies. Extensive research and development activities have been conducted for both military and civil applications. Further, various energy-absorbing seat designs have been validated through testing with anthropomorphic dummies and cadavers, and subsequently through actual accident experiences. It is apparent that the technology to produce crash-resistant seats for civil rotorcraft is currently available. A summary of seating system technology development for civil applications follows.

The need for specific types of crash resistance improvements in civil rotorcraft has been established in a number of accident studies. Snyder (Reference 49) evaluated injury statistics for civil helicopter accidents during the period 1964-1977. He concluded that impact forces and postcrash fire were significant hazards that necessitated improved occupant protection, and he called for an effort to obtain better injury information. The FAA-sponsored rotorcraft crash

dynamics study (Reference 1) examined civil helicopter accidents occurring during the five-year period 1974-1978. This study reviewed the crash environment, typical crash scenarios, and injury-causing hazards. Table 6, which is taken from Reference 1, provides a rank-order summary of injury-causing hazards for civil helicopters. The 14 hazards shown in the table were ranked according to severity and frequency of occupant injuries. As these data show, crash hazards associated with fuel systems (Hazard No. 1) and seats/restraints (Hazards No. 2, 4, 5, 9, and 12) were significant. The two studies described here conclusively identified the need for crash resistance improvements to civil rotorcraft with particular emphasis on improved seating systems.

To develop background technology for civil helicopter seating systems, the FAA Technical Center cosponsored (with the U.S. Army, Navy, and Air Force) two experimental studies of energy-absorbing seats. These studies concentrated on vertical energy absorption performance to prevent spinal injury. The first study validated the energy absorption concept through testing of a production energy-absorbing seat with human cadavers (Reference 50). This study concluded that an energy absorber limit-load of 11 G would provide significant spinal protection for the U.S. civil flying population. The second study (Reference 51) examined 13 design and testing variables that influence the performance of energy-absorbing seating systems. Each variable was isolated and parametric testing was conducted to determine the effect of these variables on seat design and occupant response.

The FAA has also been a strong proponent of analytical tools for seat design and for developing human tolerance criteria relevant to seat performance. The SOM-LA (Seat Occupant Model - Light Aircraft) program was developed under FAA Technical Center sponsorship (References 52 and 53) from 1977 to 1985. This computer program has the capability to evaluate occupant response with a range of simple to sophisticated seat models while undergoing dynamic crash loading. Evaluation of the performance of energy-absorbing seats, either analytically or in experimental testing, is based on maintaining occupant response parameters within human tolerance limits. The FAA has also sponsored two studies to analyze existing experimental and actual human tolerance data to suggest human tolerance guidelines for seat design (References 54 and 55). The culmination of this work was Advisory Circular (AC) 22-22, "Injury Criteria Human Exposure to Impact," issued in June 1985 (Reference 56).

While the basic research was evolving to design and optimize crash-resistant seating systems for civil aircraft, design teams were busy developing seats consistent with the civil marketplace. The designs ranged from sophisticated adaptations of military crash-resistant seats to innovative concepts for lower costing versions. Designs were proposed for both helicopters and general aviation aircraft, although the technological requirements are almost identical between the two aircraft types due to the similarity in the crash loads. Examples of adaptations of military-type vertically guided seats for civil applications include the pilot/copilot seats for the Bell 222 (References 57 and 58), Bell 214ST (Reference 59), and the Aerospatiale Super Puma (References 34 and 60). The general aviation community has been an advocate of lower cost energy-absorbing seats to provide a measure of spinal protection. Examples of these include seats developed by NASA (References 61 and 62), Simula Inc. (Reference 63), Piper Aircraft (Reference 64), Boeing Vertol (Reference 65), Jungle Aviation and Radio Service (JAARS) and Mission Aviation Fellowship (MAF) (Reference 66), and Cessna (Reference 67). Testing of these seats indicated that the designs met with varying degrees of success as designers developed an understanding of the complex dynamic crash environment and dynamic response of the human body.

Table 6.
Average yearly injury frequency attributable to 14 hazards for an occupant injured in a survivable rotorcraft accident

Hazard No.	Description	Moderate Injury AIS 1 or 2* (%)	Severe Injury AIS 3 or 4* (%)	Life Threatening AIS 5 or 6* (%)	Total (%)
1	Body exposed to fire when fuel system failed on impact	3.7	3.1	7.2	14.0
2	Body received excessive decelerative force when aircraft and seat allowed excessive loading	14.3	12.7	0.8	27.8
3	Body exposed to impact conditions due to inflight wire strike	0.7	1.5	5.9	8.1
4	Body struck aircraft structure because design provided inadequate clearance and/or restraint allowed excessive motion	33.7	2.0	1.2	36.9
5	Body struck aircraft structure due to lack of upper torso restraint	15.3	4.6	0.8	20.7
6	Body drowned because injuries prevented escape from aircraft	0.0	0.0	3.3	3.3
7	Body struck aircraft structure because restraint was not used properly	1.2	0.7	1.2	3.1
8	Body struck aircraft structure when structure collapsed excessively	5.1	0.7	0.0	5.8
9	Body struck aircraft structure when seat failed	0.7	0.8	0.4	1.9
10	Body struck by external object when main rotor blade entered occupiable space	0.0	0.0	0.7	0.7
11	Body struck by external object when object (other than main rotor blade) entered occupiable space	0.9	0.4	0.4	1.7
12	Body struck aircraft structure when restraint system failed	0.0	0.8	0.0	0.8
13	Body injured during postcrash egress	1.2	0.0	0.0	1.2
14	Body exposed to chemical agents on impact	0.8	0.0	0.0	0.8
	TOTAL	77.6	27.3	21.9	126.8**

*Based on the Abbreviated Injury Scale, 1980 revision, American Association for Automotive Medicine, Morton Grove, Illinois.
**Percentage exceeds 100 percent due to the occurrence of multiple occupant injuries.

As the technology developed to design and test crash-resistant seats for civil rotorcraft, an industry group was convened to recommend realistic crash resistance criteria for future civil helicopters. The Rotorcraft Airworthiness Requirements Committee (RARC) of the Aerospace Industries Association (AIA) established a special Crashworthiness Project Group to develop and recommend these criteria. The results of this group's work consisted of recommendations for energy-absorbing seats, restraints, and crash-resistant fuel systems. Summaries of this work can be found in References 68 and 69.

The RARC Crashworthiness Project Group recommended installation of energy-absorbing seats equipped with upper torso restraint systems. A vertical impact velocity criterion of 26 ft/sec was recommended by the group based on the statistical impact data from Reference 1. The recommended upper torso restraint criterion was in accordance with a newly developed Society of Automotive Engineers (SAE) aeronautical standard, AS-8043, Aircraft Torso Restraint System, Suitable for Both Fixed and Rotary-Wing Aircraft (Reference 70). Two dynamic seat qualification tests were also recommended by the Crashworthiness Project Group. The first was a forward impact test at 10 degrees yaw with an 18.4-G peak triangular pulse and a 42-ft/sec velocity change. The second was a vertical impact test with the seat pitched 30 degrees nose down, a 30-G peak triangular pulse, and a 30-ft/sec velocity change to provide the 26-ft/sec velocity component perpendicular to the aircraft floor. The recommendations of the Crashworthiness Project Group were submitted to the FAA as the rotorcraft industry position.

The FAA was also active in developing minimum seat performance standards for newly certificated rotorcraft. Based on the extensive FAA-sponsored research in this area, and the recommendations of the RARC committee, a Notice of Proposed Rulemaking (NPRM) on "Occupant Restraint in Normal and Transport Category Rotorcraft," Notice No. 87-4, was issued for comments in June 1987 (Reference 71). Subsequently, new rules were promulgated requiring dynamic testing of seats for newly certificated rotorcraft (Reference 72).

The recently issued rules for dynamic seat performance are already having an impact on rotorcraft design. The light-twin BO 108 helicopter being developed by Messerschmitt-Bolkow-Blohm GmbH (MBB) in Germany is incorporating pilot and passenger seats capable of meeting these requirements. Similarly, the McDonnell Douglas Helicopter Company's (MDHC) MD-900 will incorporate crash-resistant pilot and passenger seats. And finally, the Army is considering adoption of these criteria for its new training helicopter (NTH) that it intends to procure in the early 1990's. This is significant since the Army has selected the FAA requirements over those of MIL-S-58095A(AV) (Reference 73) for the seat performance requirements in this proposed adaptation of an off-the-shelf commercial helicopter.

3.5 FUEL SYSTEM TECHNOLOGY

The development of fuel system technology closely parallels the development of crash-resistant seating systems over the last 20 years. The impetus for crash-resistant fuel system development came from extensive postcrash fires in U.S. Army helicopters in Vietnam in the late 1960's. In 1968, the Army committed itself to eliminating postcrash fires in survivable helicopter crashes. A report by Knapp, Allemond, and Kearny (Reference 74) clearly defined the magnitude of the problem. Table 7, taken from this report, shows fatalities and injuries in UH-1 and AH-1 helicopters during the three-year period of 1967 to 1969. Postcrash fires were noted in 13.3 percent of the survivable accidents and resulted in 95 fatalities and 64 injuries.

Table 7. 1967 - 1969 fatalities and injuries in survivable Army rotorcraft crashes* (Reference 74)				
	Fatalities		Injuries	
Aircraft	Thermal	Nonthermal	Thermal	Nonthermal
UH-ID	47	106	32	718
UH-IH	47	49	25	530
AH-IG	1	4	7	49
Total	95	159	64	1,297

*1,000 accidents, no crash-resistant fuel systems, 133 postcrash fires.

Through a rapid engineering development program, CRFS's were introduced into the Army fleet for aircraft considered to be at highest risk. Table 8, from the report by Knapp et al., shows the influence of CRFS's on postcrash survivability during the seven-year period of 1970 to 1976. Significantly, the aircraft that had been retrofitted with CRFS's (which were the highest risk aircraft) demonstrated a 1.3 percent incidence of postcrash fire compared to 3.7 percent for the remainder of the fleet. In the helicopters equipped with CRFS's, there was a 75-percent reduction in thermal injuries and elimination of thermal fatalities. The Army has conclusively demonstrated the ability of CRFS's to minimize the hazard from postcrash fires.

Table 8. 1970 - 1976 Army rotorcraft crash fatalities and injuries (Reference 74)				
	Survivable Accidents		Nonsurvivable Accidents	
Classification	w/o CRFS	w CRFS	w/o CRFS	w CRFS
Thermal injuries	20	5	5	0
Nonthermal injuries	529	386	13	28
Thermal fatalities	34	0	31	1
Nonthermal fatalities	120	44	279	85
Accidents	1,160	1,258	61	32
Postcrash fires	43	16	42	18

The U.S. civil helicopter fleet has experienced almost the same postcrash fire levels as the Army did prior to retrofitting CRFS's. For the years 1974 to 1978, the civil helicopter fleet had a postcrash fire rate of 13.8 percent (Reference 1). Table 9 shows a comparison of injuries and fatalities in survivable accidents for unmodified Army helicopters (Reference 74) and civil helicopters (Reference 1).

Table 9.
Injuries and fatalities in survivable accidents for rotorcraft not equipped with crash-resistant fuel systems

Sample	Injuries		Fatalities		Percentage of Injuries and Fatalities Caused by Fire
	Thermal	Nonthermal	Thermal	Nonthermal	
U.S. Army Helicopters 1967-1969 1,000 accidents 133 postcrash fires	64	1,297	95	159	10.9
U.S. civilian helicopters 1974-1978 86 accidents with known injuries	13	174	18	42	14.4

The Army has been successful in minimizing the postcrash fire hazard through development and retrofit of crash-resistant fuel systems. However, this technology is not directly transferrable to civil helicopters due to the differing design requirements. The most significant differences are the ballistic tolerance requirement for Army fuel bladders and the need for high levels of cut, tear, and puncture resistance to survive the higher impact velocities of the Army crash environment. These two conditions significantly influence construction and weight of the military CRFS.

Research and design programs to develop CRFS's for civil helicopters have not kept pace with the military programs. However, Goodyear suggested some early design concepts for helicopters and general aviation aircraft (Reference 75). BHTI used its experience in developing the UH-1 retrofit CRFS to develop one for the model 222 (Reference 57). The BHTI system for the model 222 uses Uniroyal fuel bladders tested to 56-ft/sec free-falls without rupture. Fuel lines and vent lines also have breakaway fittings to minimize the possibility of postcrash fire due to fuel spillage.

The FAA has sponsored development and testing of CRFS's for use in general aviation aircraft (References 76 and 77). In 1979 and 1980, retrofit CRFS's were developed for four small fixed-wing aircraft operated by the Mission Aviation Community (Reference 78). This report provides an excellent overview of the approach used to develop a CRFS. Aerospatiale has also used CRFS design concepts to develop systems capable of meeting a range of impact requirements (Reference 34). Both fuel tanks and interconnections were examined in this study, as well as the interaction of the fuel tank with surrounding structure.

The need for improvement in the crash resistance of civil helicopter fuel systems has been established by a number of studies. Voluntarily, some manufacturers have been exceeding the FAA minimum standards for fuel system design to enhance the safety of their aircraft. However, a CRFS is expensive to develop and install, and can result in a significant weight penalty. The effect in the competitive marketplace is that the manufacturer who installs an

enhanced fuel system may be at a disadvantage in selling its aircraft (unless the buyer is knowledgeable and specifically looking for crash-resistant features). As a result of this dilemma, the Rotorcraft Airworthiness Requirements Committee (RARC) of AIA has tasked the Crashworthiness Project Group with developing new fuel system criteria. The group has used MIL-T-27422B (Reference 79) as a model with each individual design criteria suitably adjusted for civil helicopters. Reference 68 presents an overview of these recommendations which were submitted to the FAA and considered in promulgating Notice 90-24 (Reference 80).

3.6 SURVEY OF CRASH-RESISTANT CIVIL ROTORCRAFT DESIGNS

The previous sections demonstrate that crash resistance features are finding their way into civil rotorcraft. Surveys of crashes indicate that these features are reducing injuries associated with crashes. Figure 10 compares the mean time between serious injury for various types of aircraft (Reference 81). This chart was prepared to show the relative risk of BHTI civil rotorcraft designs compared to other rotorcraft and fixed-wing aircraft. The chart indicates that the incorporation of crash resistance features in the models 222, 412, and 214ST has resulted in increasingly safer helicopters whose crash resistance surpass most types of general aviation aircraft.

Technical papers indicate that BHTI exhibits a philosophy of providing helicopters with crash resistance features. This philosophy results in a concerted effort to develop crash resistance features with the goal of publicizing the positive results that can be achieved with these features. Specifically, BHTI has developed a range of CRFS's, energy-absorbing seats, and upper torso restraint systems. Table 10 shows a survey of CRFS availability as of 1985 (Reference 68). At that time, BHTI had CRFS's available for eight civil rotorcraft designs. Also, BHTI had developed energy-absorbing seating systems with upper torso restraint for its 222, 412, and 214ST models. The incorporation of these crash resistance features was not without penalty. Table 11 shows a breakdown of the weight penalty associated with these features in the BHTI helicopter (Reference 80).

Table 10.
Availability of crash-resistant fuel systems in
civil rotorcraft as of December 1985 (Reference 68)

Manufacturer/Model	Standard Equipment	Kit Available
BHTI 214B	X	
BHTI 206BIII (with 91-Gallon Tank)	X	
BHTI 206L-3	X	
BHTI 222	X	
BHTI 222B	X	
BHTI 222UT	X	
BHTI 412	X	
BHTI 214ST	X	
Boeing Vertol 234	X	
Sikorsky S-70	X	
Sikorsky S-76		X
Aerospatiale AS 332L Super Puma		X

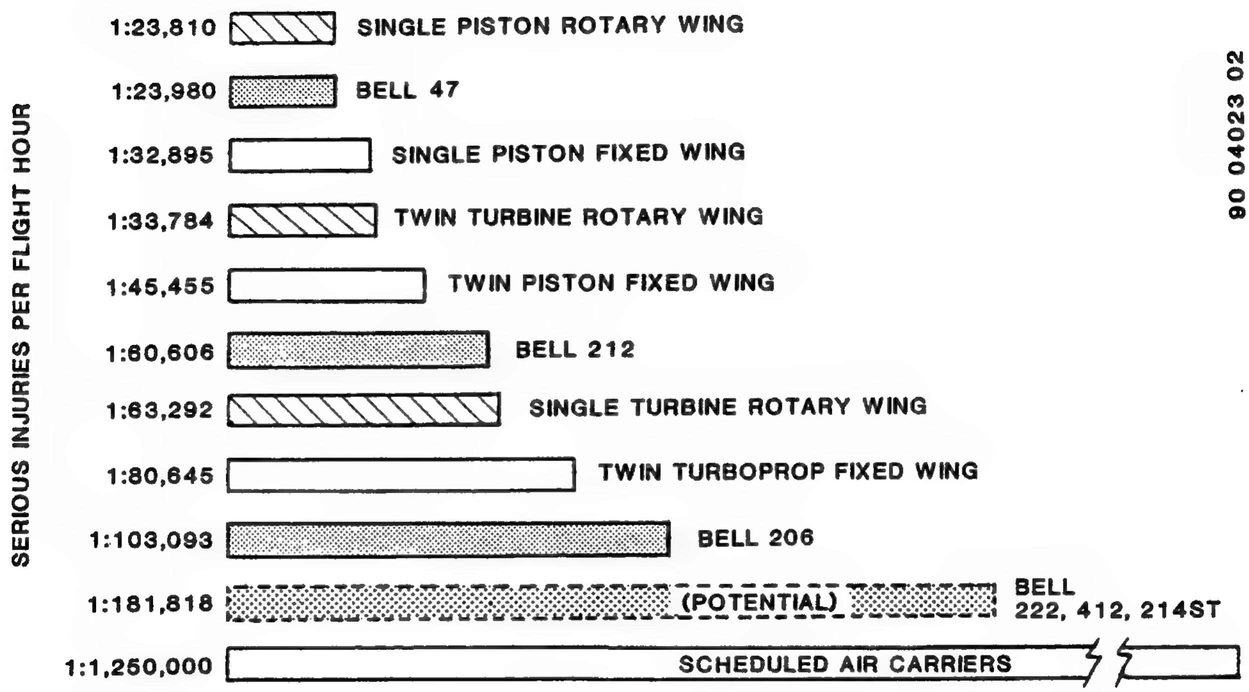


Figure 10.
Mean time between serious injury for various aircraft types (Reference 80).

Table 11.
Weight penalty of crash safety features in
BHTI helicopters (Reference 81)

	Weight Penalty (lb)		
BHTI Model	222	412	214ST
Passenger's shoulder harness and energy-attenuating seats	55	122	161
Crash-resistant fuel system	28	35	50
	83	157	211
Percentage of gross weight	1.1%	1.4%	1.2%

Other manufacturers have also been active in promoting crash resistance principles. As Table 10 indicates, both Boeing and Sikorsky have developed CRFS designs for one of their commercial helicopters. In Europe, both Aerospatiale and MBB have developed the capability to incorporate crash resistance features. Aerospatiale developed this capability through crash testing of an SA 330 Puma (Reference 60) and an SA 341 Gazelle (Reference 34). The purpose of these tests was to develop a general understanding of crash behavior and to validate the KRASH code for future work. Aerospatiale has used this capability to develop crash protection systems for the AS 332 Super Puma and SA 365 Dauphin. The Super Puma design includes reinforced airframe, enhanced landing gear, CRFS, and energy-absorbing seats. The Dauphin has a reinforced airframe, high-strength seats, and a CRFS. Although these aircraft are generally intended for military use, the technology that has been developed would have direct application to commercial variants.

MBB has also been active in developing crash resistance technology. The light-twin BO 108 currently under development will feature energy-absorbing seats for all occupants. In conjunction with MBB, Kawasaki Heavy Industries (KHI) of Japan has developed the twin-engine BK-117 helicopter. In March 1985, KHI conducted a crash test of this helicopter to evaluate its structural integrity under impact conditions (Reference 82). Also, the test was intended to verify modeling of the airframe with program KRASH.

The most recent civil rotorcraft program is the commercial MD-900 twin-engine helicopter being developed by McDonnell Douglas Helicopter Company (MDHC). The MD-900 will incorporate many advanced features such as the company's NOTAR™ (No Tail Rotor) antitorque system. Although still in the design phase, the preliminary configuration includes a number of features to enhance crash safety. These features include energy-absorbing seats for all occupants, two keel beams with antiplowing beams in the cockpit area, modified A-frame construction with high-mass item retention, and a heavy-duty, bladder-type fuel cell with frangible fittings. The consideration of these features is significant since MDHC is seeking a new certification for this helicopter.

The survey of applicable crash resistance technology would not be complete without mention of the design and development work being conducted for general aviation aircraft. The technology developed for these aircraft is almost directly applicable to civil rotorcraft. Extensive

work has been conducted in the areas of crash-resistant seats, CRFS's, and fuselage structural dynamics. Further, the General Aviation Manufacturer's Association (GAMA) and the industry/Government group called the General Aviation Safety Panel (GASP) have been active in proposing improved safety standards (References 83 and 84).

It is apparent from the survey of crash-resistant rotorcraft designs that applicable technology is evolving for civil rotorcraft. Whereas military rotorcraft have incorporated extensive crash resistance features by direction, the civil marketplace has been slower to identify the need for improved crash resistance. It is equally apparent from the survey that the incorporation of crash resistance technology in civil rotorcraft will require innovative design solutions that minimize cost and weight. Based on historical trends found in the survey, it is likely that the greatest advances in overall crash-resistant rotorcraft design will come with newly certificated models.

4.0 CONCEPTUAL CRASH-RESISTANT ROTORCRAFT DESIGNS

4.1 APPROACH

Major improvements in the crash resistance of the civil rotorcraft fleet will most likely occur through the development of new aircraft models. The regulatory approach used by the FAA is to develop improved safety standards that apply to newly certificated models after a specified future date. The time delay between enactment of a new rule and effectivity of the rule allows manufacturers to incorporate appropriate technology into new aircraft designs. If the new technology can be incorporated as the aircraft is being developed, then a reduced weight and cost impact can be achieved.

This study considered the effect of incorporating improved crash resistance into future civil rotorcraft designs. To evaluate the effect on future rotorcraft, conceptual designs were developed to represent the next generation of civil rotorcraft. Three generic rotorcraft designs were developed by a team of designers and engineers from Simula Inc., BHTI, and Sikorsky Aircraft to represent typical design features and dimensions of three weight classes of civil helicopters. Various levels of crash resistance were incorporated into the conceptual generic rotorcraft to determine the associated weight penalty.

4.1.1 Selection of Conceptual Designs

The U.S. rotorcraft fleet was evaluated to determine type and quantity of currently registered helicopters (Reference 85). A tabulation of the registered helicopters by manufacturer and type is shown in Table 12. The helicopter fleet data was divided into the four gross weight categories, designated A, B, C, and D, used in Reference 1 (see Table 13). A summary of the U.S. helicopter fleet shown by weight class is presented in Table 14.

It was decided early in the study that development of conceptual rotorcraft designs would be limited to models falling into weight classes B, C, and D. As Table 14 shows, this group encompasses all rotorcraft exceeding 2,500-lb maximum gross take-off weight. Weight classes B, C, and D accounted for 70 percent of the U.S. civil rotorcraft fleet registered in October 1988. The remaining 30 percent of the fleet falls into weight class A, which is for helicopters at or below 2,500-lb maximum gross weight.

Development of conceptual designs was limited to B, C, and D weight classes due to the scope of the defined program from the FAA. These three weight classes were selected because of the existing background in incorporating crash resistance features into various civil and military aircraft of similar size. The research team concluded that parametric trends in design and cost variables would be applicable to weight class A rotorcraft and thus the data could be extrapolated for the purposes of this study. However, it was felt that the actual design techniques to achieving improved crash resistance in these small rotorcraft may be different than in the other weight classes. The primary obstacle facing the design team was the relative lack of existing crash-tolerant hardware design concepts for rotorcraft of less than 2,500 lb DGW. It was therefore concluded that the development of design concepts for weight class A would have to be the subject of a more in-depth study that included hardware development.

Table 12.
U.S. civil rotorcraft fleet as of October 1988 (Reference 85)

Manufacturer	Model/ Series*	Type of Engine**	No. of Engines	No. of Aircraft
Aerospatiale	SA 315B	Turbine	1	68
	SA 316/318/319	Turbine	1	76
	SA 330	Turbine	2	13
	SA 332	Turbine	2	5
	SA 341	Turbine	1	39
	AS 350	Turbine	1	289
	AS 355	Turbine	2	170
	SA 360	Turbine	1	10
	AS 365	Turbine	2	16
			Total Aerospatiale	**686**
Agusta	A 109	Turbine	2	86
			Total Agusta	**86**
Bell	47/13	Recip	1	1,496
	204/205/UH1	Turbine	1	267
	206A/B	Turbine	1	1,648
	206L	Turbine	1	654
	212	Turbine	2	145
	214	Turbine	1	34
	222	Turbine	2	111
	301	Turbine	2	2
	412	Turbine	2	60
			Total Bell	**4,417**
Boeing	107	Turbine	2	16
	CH 47	Turbine	2	5
	234	Turbine	2	5
	360	Turbine	2	1
	HUP	Recip	1	3
	PV18	Recip	1	1
	H21	Recip	1	12
	42A	Recip	1	1
			Total Boeing Vertol	**44**
Enstrom	F-28	Recip	1	359
	280	Recip	1	159
			Total Enstrom	**518**
Hynes (Brantly)	H2	Recip	1	155
	H5	Recip	1	15
			Total Hynes	**170**

*Series designations incorporate all like variants.
**Designates two types of engines: turbine and reciprocating piston-type.

Table 12 (contd).
U.S. civil rotorcraft fleet as of October 1988 (Reference 85)

Manufacturer	Model/ Series*	Type of Engine**	No. of Engines	No. of Aircraft
MBB	BO 105	Turbine	2	143
	BK 117	Turbine	2	63
			Total MBB	**206**
McDonnell Douglas	369/500	Turbine	1	746
			Total McDonnell Douglas	**746**
Robinson	R-22	Recip	1	365
			Total Robinson	**365**
Rogerson/Hiller	UH-12	Turbine	1	19
	UH-12	Recip	1	748
			Total Rogerson/Hiller	**767**
Schweizer (Hughes)	269	Recip	1	779
			Total Schweizer	**779**
Sikorsky	S-56/H37	Recip	2	47
	S-51	Recip	1	9
	S-52	Recip	1	16
	S-55	Recip	1	131
	S-58/H34	Recip	1	198
	S-61/H-3	Turbine	2	33
	S-62	Turbine	1	6
	S-64	Turbine	2	7
	S-70	Turbine	2	1
	S-72	Turbine	2	2
	S-76	Turbine	2	183
			Total Sikorsky	**633**
Westland	WG-30	Turbine	2	9
			Total Westland	**9**
			TOTAL U.S. FLEET	**9,426**

*Series designations incorporate all like variance.
**Designates two types of engines: turbine and reciprocating piston-type.

Table 13.
Four weight class categories
for U.S. civil rotorcraft fleet

Weight Class	Maximum Gross Take-Off Weight (lb)
A	< 2,500
B	2,501 - 6,000
C	6,001 - 12,500
D	> 12,500

4.1.2 Conceptual Design Approach

A generic rotorcraft design was prepared for each of the three weight classes (B, C, and D). The generic helicopters were developed as a composite of design features and dimensions representative of each weight class. The generic rotorcraft, all of which were conventional helicopters, were identified as light, medium, and heavy. Scale line drawings of each of the three generic helicopters are shown in Figure 11.

The preliminary configuration for each of the three generic helicopters was prepared by Simula Inc. The most recent rotorcraft designs in each of these three weight classes were examined to determine trends in design parameters such as gross weight, cabin dimensions, seating configuration, engine configuration, structural design, fuel capacity, and rotor characteristics. The preliminary configurations were then examined by a combined engineering group from BHTI and Simula. Structural details were developed by this group. The structural design for each generic helicopter was used to assess fuselage and landing gear weight penalties. The structural design was also used by Sikorsky Aircraft as a baseline for incorporating CRFS's and by Simula for incorporation of crash-resistant seating systems.

4.2 GENERIC ROTORCRAFT DESIGNS

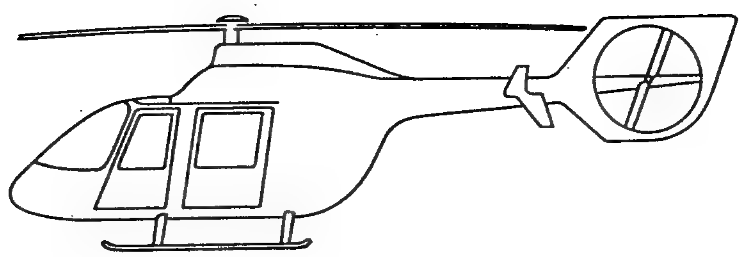
This section contains details of conceptual designs for the three generic rotorcraft.

4.2.1 Generic Light Rotorcraft

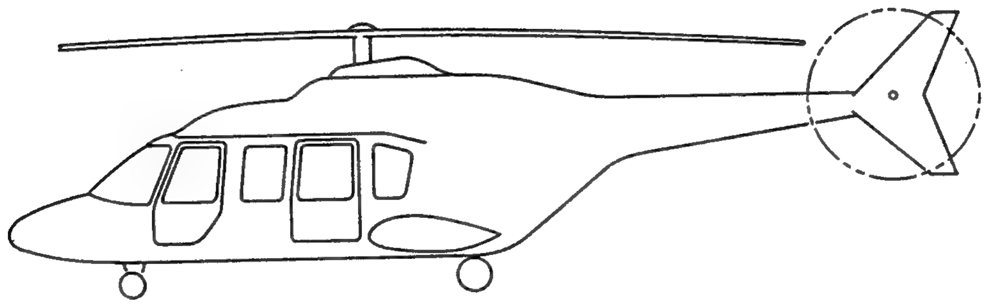
The generic light rotorcraft is a single engine, five-place design. It has a maximum take-off weight of 4,100 lb with a 105-gal fuel system capacity. The range for this design is estimated to be 340 miles at normal cruise speed. Figure 12 shows the overall configuration and dimensions for the design. Additional structural details for the generic light rotorcraft are shown in Figure 13.

Table 14.
U.S. civil rotorcraft by weight class as of October 1988

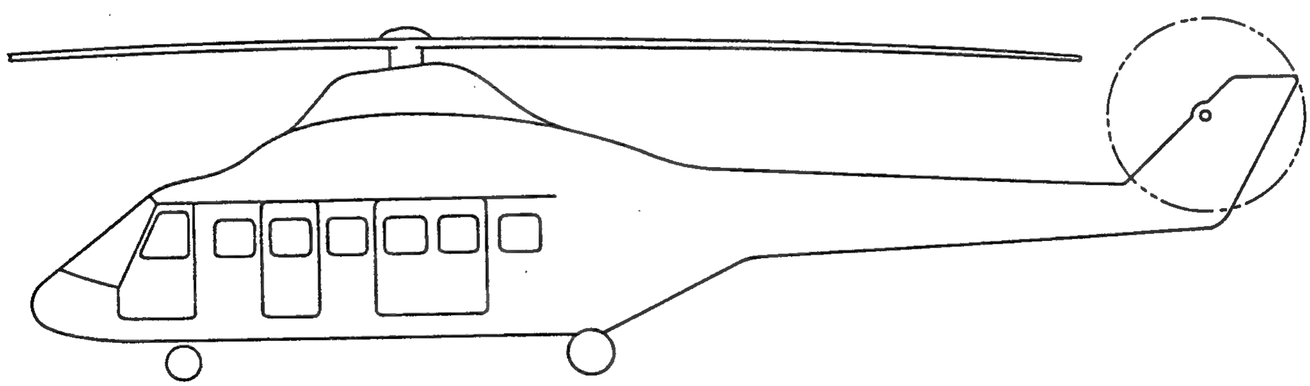
Weight Class	A	B	C	D
Maximum Gross Take-off Weight (LB)	<2,500	2,501-6,000	6,001-12,500	>12,500
Manufacturer and model (quantity registered is shown in parentheses)	Bell 47 (1,496) Hynes H^2 (155) Robinson R-22 (365) Schweizer 269 (779)	Aerospatiale 315,316,318, 319,341,350, 355 (642) Augusta 109 (86) Bell 206 (2302) Enstrom F-28, 280 (518) Hynes H5 (15) MBB 105 (143) MDHC 500 (746) Rogerson/Hiller UH-12 (767)	Aerospatiale 360,365 (26) Bell 204,205 222, 412 (583) Boeing HUP, H21, 42A (17) MBB BK117 (63) Sikorsky S-56, S-51, S-52, S-55 S-62, S-76 (392)	Aerospatiale 330,332 (18) Bell 214,301 (36) Boeing 107, 234, 360 (27) Sikorsky S-58, S-61, S-64, S-70 S-72 (241) Westland 30 (9)
Total in Weight Class	2,795	5,219	1,081	331



(a) Light
(Representing weight class B: 2,501-6,000 lb DGW)



(b) Medium
(Representing weight class C: 6,001-12,500 lb DGW)



(c) Heavy
(Representing weight class D: Greater than 12,500 lb DGW)

Figure 11.
Three generic rotorcraft representing the U.S. civil fleet.

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The preliminary design had two locations available for fuel: a single vertical tank aft of the crewseats and an L-shaped tank enclosed in the structure forming the rear three-place passenger seat. These available fuel locations are shown in the cross-hatched area in Figure 12. Three fuel system designs were examined for the light rotorcraft. Figures 14a, b, and c show the three potential fuel system configurations. In Figure 14a, the fuel system incorporates two tanks, one located aft of the crewseats and an L-shaped tank formed to the shape of the aft three-place bench seat. The system in Figure 14b differs from that in 14a in the shaping of the aft tank to eliminate fuel under the seat. The final configuration, shown in Figure 14c, has a large single fuel tank located aft of the rear seat.

A trade-off study was conducted to compare the three fuel system designs. It examined factors such as system complexity, cost, weight, crash resistance, and maintenance of aircraft center of gravity (c.g.) as fuel is expended. The third system, shown in Figure 14c, achieved the best overall performance in meeting these factors. It demonstrated excellent crash resistance at a reduced weight and cost; however, consideration of the aircraft c.g. would have to be taken into account since all of the fuel is aft of the aircraft c.g. A schematic diagram of the selected fuel system is shown in Figure 15.

The seats for the generic light rotorcraft consist of two seats in the front and an aft three-place bench seat. The front seats achieve vertical energy absorption through a pivoting mechanism at the rear of the seat. The aft bench seat also incorporates energy absorption through a four-bar linkage mechanism. The maximum available space for seat stroke and depth of the seat pan and cushions is 11 in. The aft seat is designed for three 50th-percentile adult male occupants. The seat absorbs crash energy while deforming forward and down. The maximum vertical stroke distance is approximately 6 in. Line drawings of the front and rear seat concepts are shown in Figure 16.

4.2.2 Generic Medium Rotorcraft

The generic medium rotorcraft conceptual design is a 12-place configuration: two crew and 10 passengers. The rotorcraft is a twin-engine configuration with 245 gal of usable fuel. The design is estimated to have a range of 462 miles at normal cruise speed. Figure 17 shows the overall configuration of the generic design. Additional structural details are shown in Figure 18.

The fuel system design features four individual cells. Two of the four cells are located behind the aft-most, four-passenger seat. The remaining two fuel cells are located in sponsons outboard of the aft seat. The configuration of the fuel system and location of the major fuel system components are shown in Figure 19. A schematic diagram of the generic medium rotorcraft fuel system is presented in Figure 20.

The seating system configuration uses three different seat types. The two seats in the cockpit area are freestanding, floor-mounted designs with vertical and fore/aft adjustment. The cabin area has two sets of three-place, freestanding seats and two, two-place seats which are mounted to the floor and bulkhead. Each cabin seating location has a lap belt and diagonal shoulder harness, while the cockpit seats have lap belts and dual shoulder harnesses. Schematic drawings of the three seat types are shown in Figure 21.

4.2.3 Generic Heavy Rotorcraft

The generic heavy rotorcraft is designed for 17 passengers and a crew of two, as shown in Figure 22. Maximum gross take-off weight for this passenger configuration is 16,200 lb. The aircraft has two engines with a fuel capacity of 380 gal resulting in a normal cruise range of 415 miles. Major structural details are shown in Figure 23.

The CRFS conceptual design for this rotorcraft is shown in Figure 24. This design incorporates two large fuel cells: one aft of the cockpit and one aft of the cabin section. Each fuel cell is shaped to form the backrest for four seat positions. A schematic diagram of the fuel system is shown in Figure 25.

The seating configuration has four different seat types. In the cockpit there are two single seats with vertical and fore/aft adjustment. The cabin area has three different seat types: three free-standing single seats, three free-standing two-place seats, and four floor- and bulkhead-mounted two-place seats. All seats in the aircraft have vertical energy absorption, and lap belt and shoulder harness restraints. The designs of the free-standing single and two-place seats are shown in Figure 26. The four two-place seats shown in the cabin area are similar to those shown in Figure 21 for the medium rotorcraft design.

A	4'-7"
B	9'-7"
C	7'-3"
D	5.5"
E	50"
F	14.5"
G	18.5"
H	30'-0"

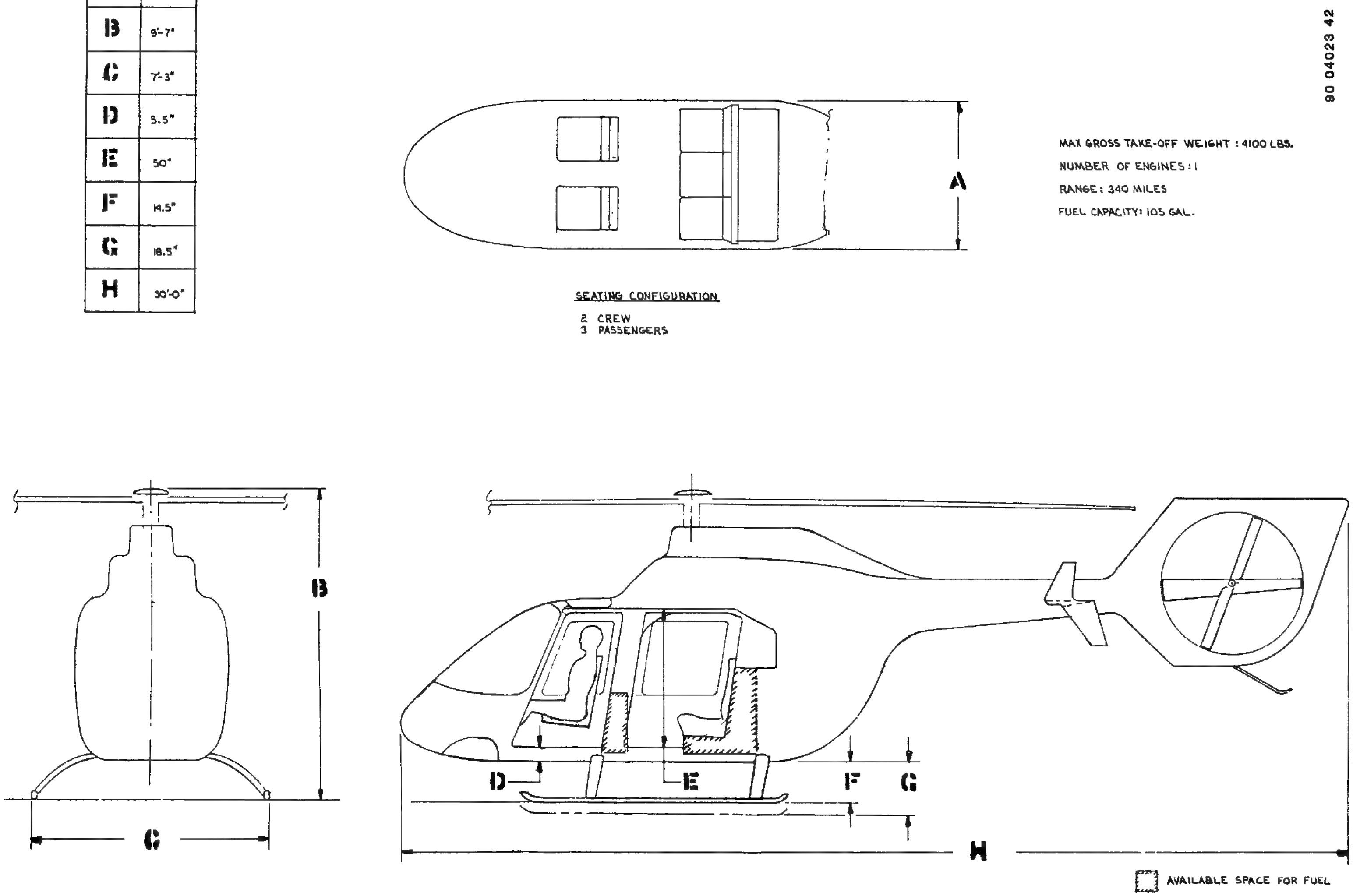


Figure 12.
Overall configuration and dimensions of the generic light rotorcraft.

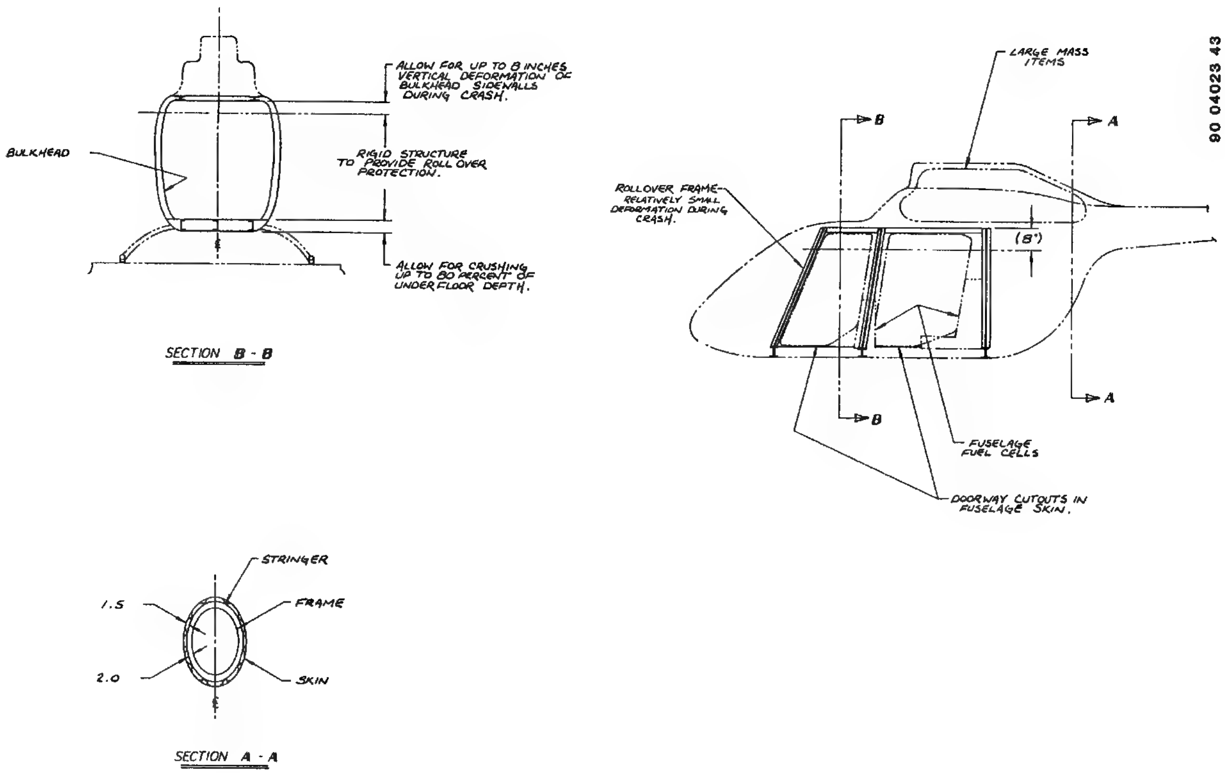


Figure 13.
Structural details for the generic light rotorcraft.

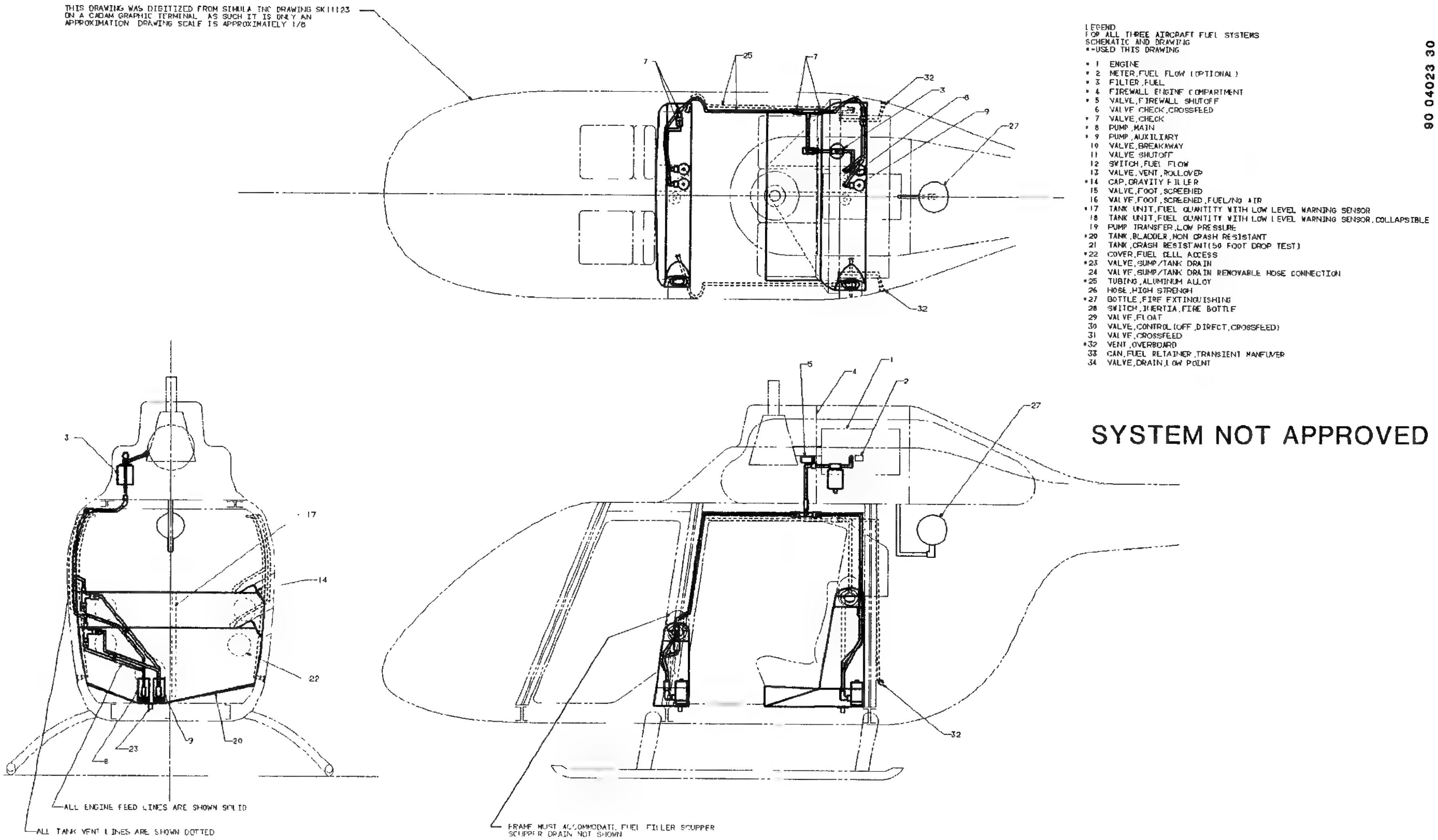


Figure 14a.
Fuel system configuration 1 for the generic light rotorcraft.

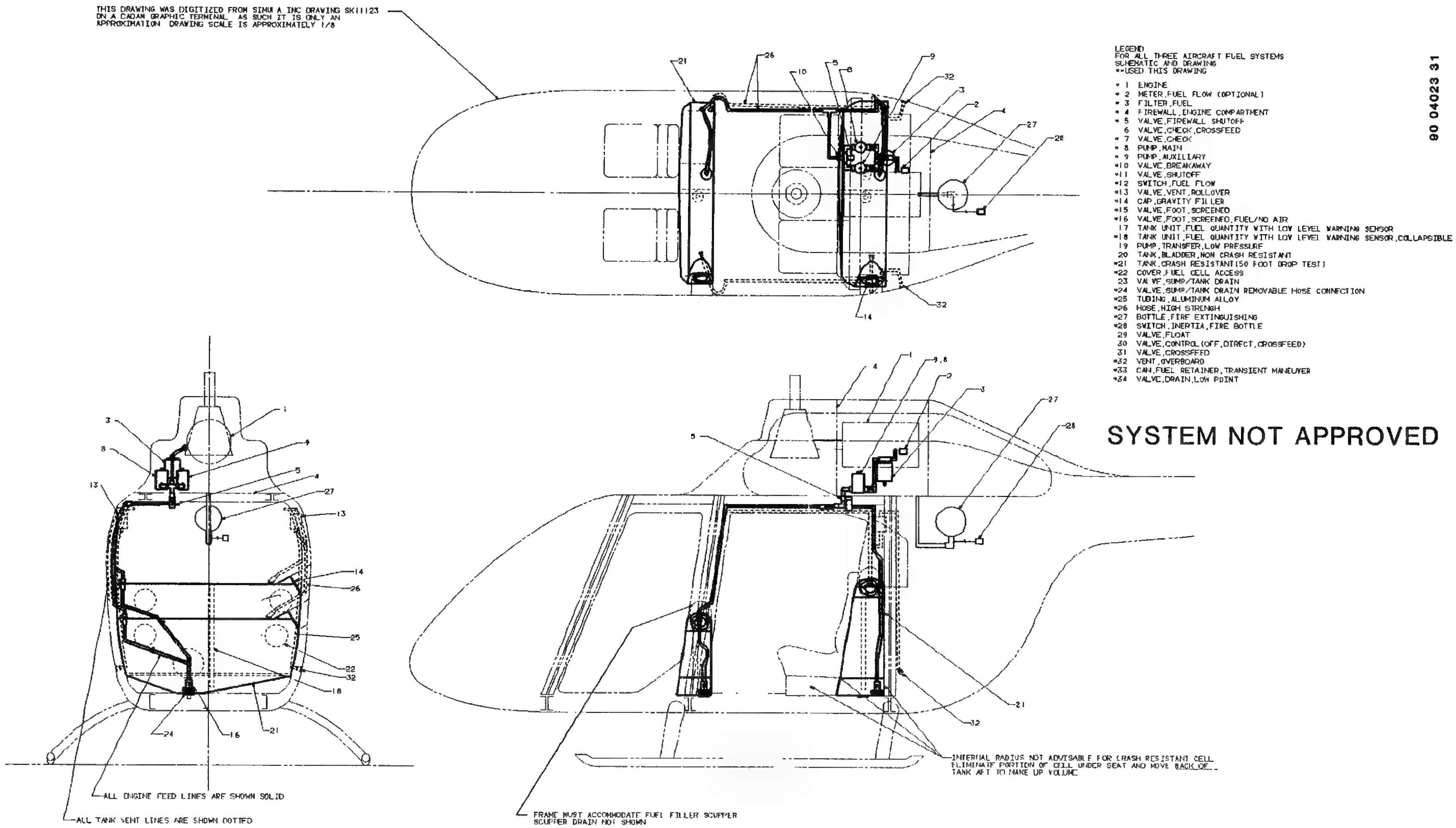


Figure 14b.
Fuel system configuration 2 for the generic light rotorcraft.

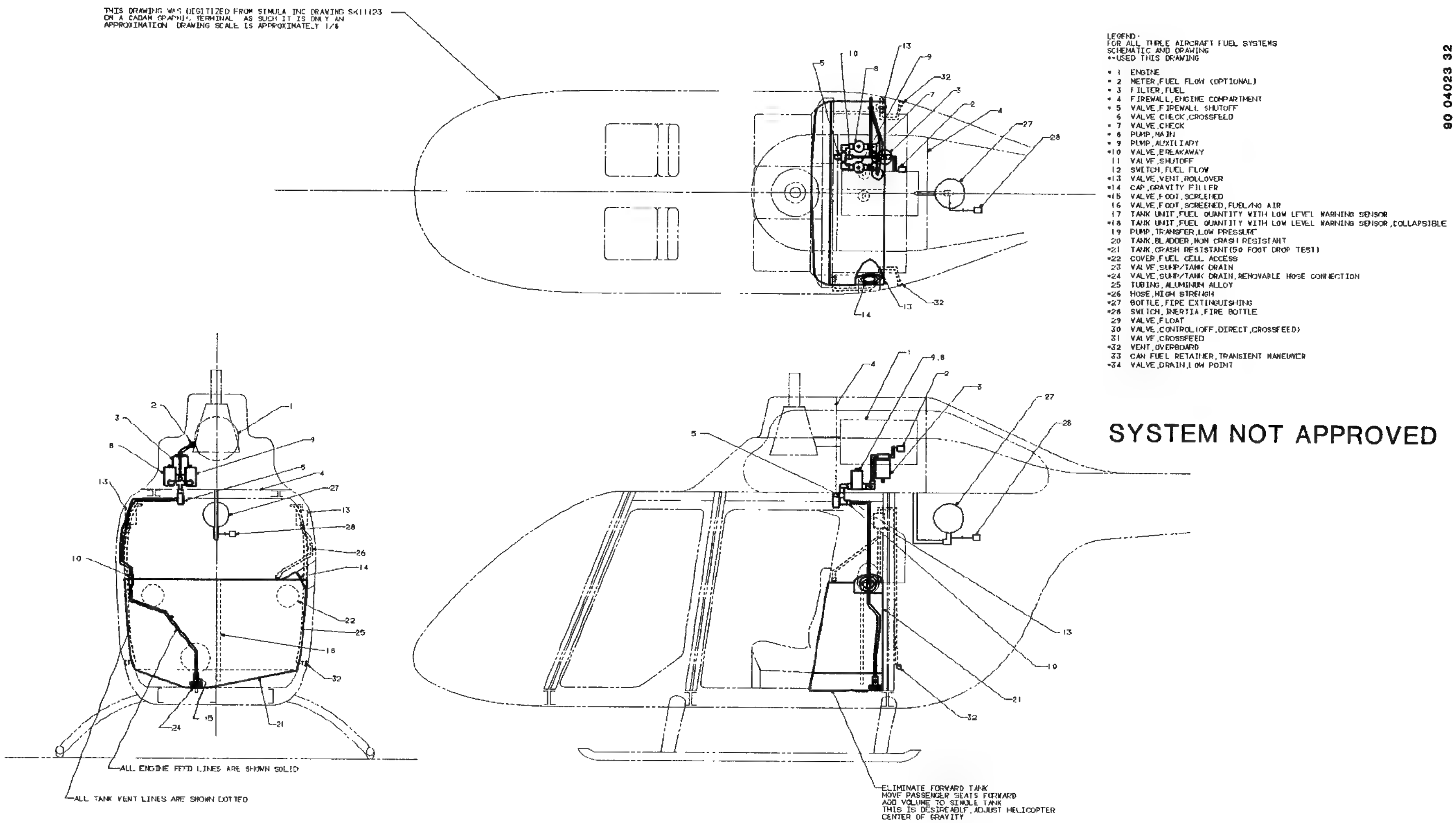
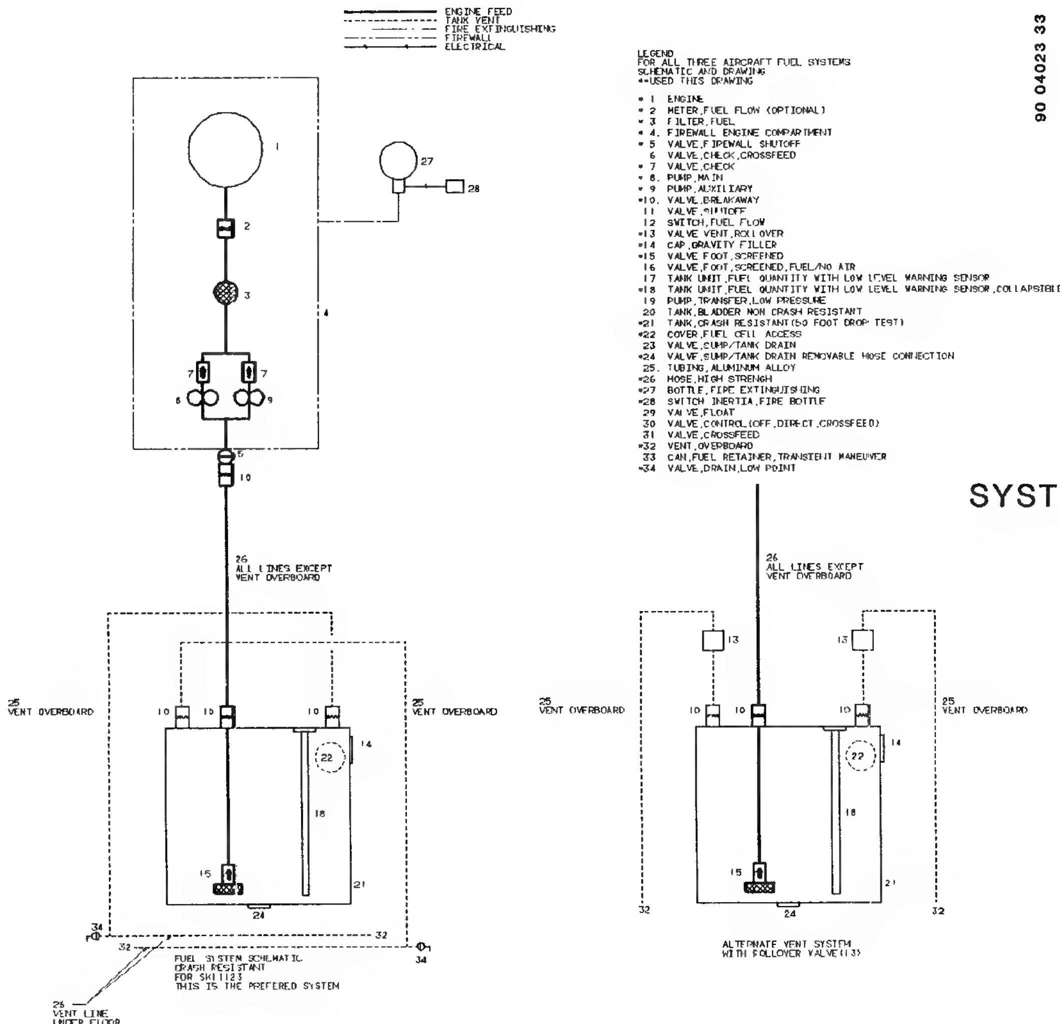


Figure 14c.
Fuel system configuration 3 for the generic light rotorcraft.



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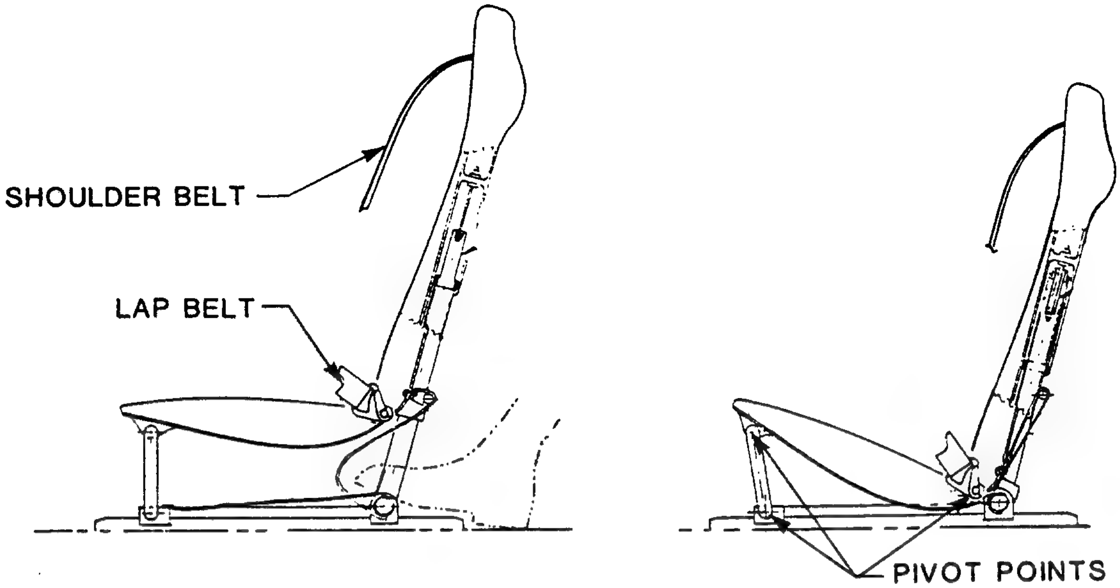
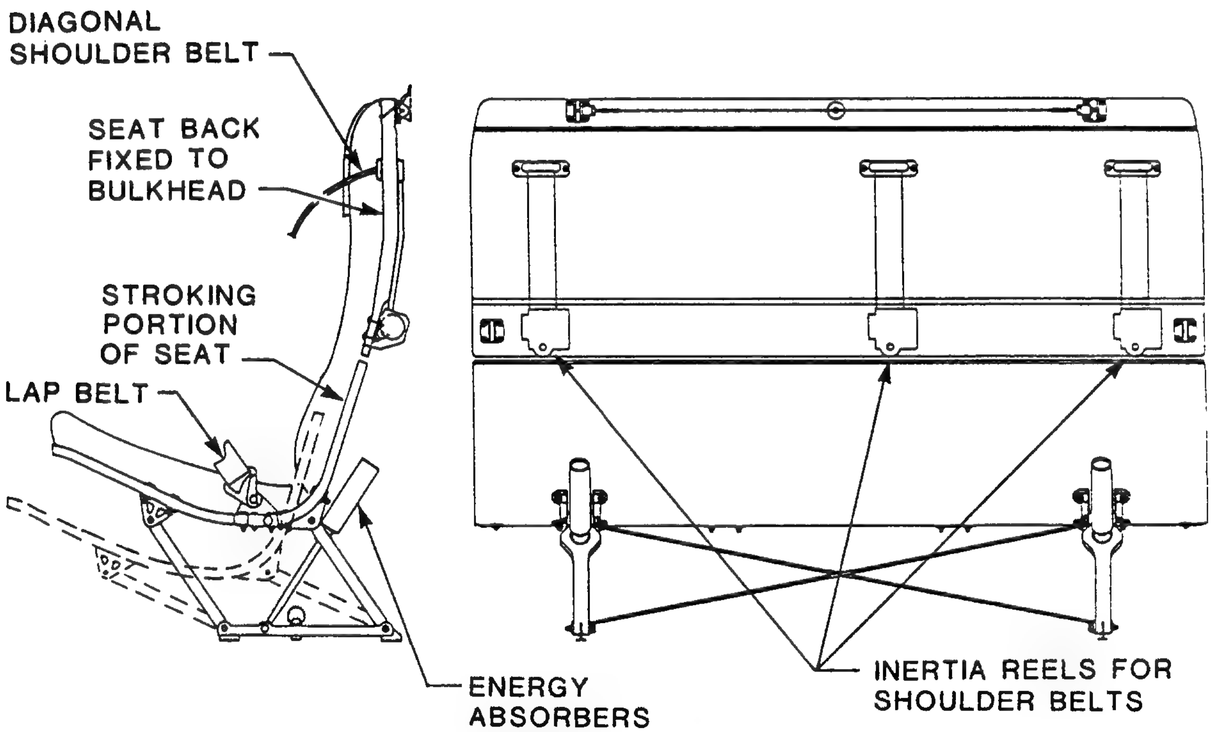
SYSTEM NOT APPROVED

Figure 15.
Schematic diagram of the selected fuel system (No. 3) for the generic light rotorcraft.



(a) Free-standing, floor-mounted pilot/copilot seat.



(b) Three-place passenger seat with combined floor and bulkhead mounting.

Figure 16.
Seat concepts for the generic light rotorcraft.

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A	6'-0"
B	11'-0"
C	7'-11"
D	9.2"
E	53"
F	13.4"
G	21.4"
H	38'-10"

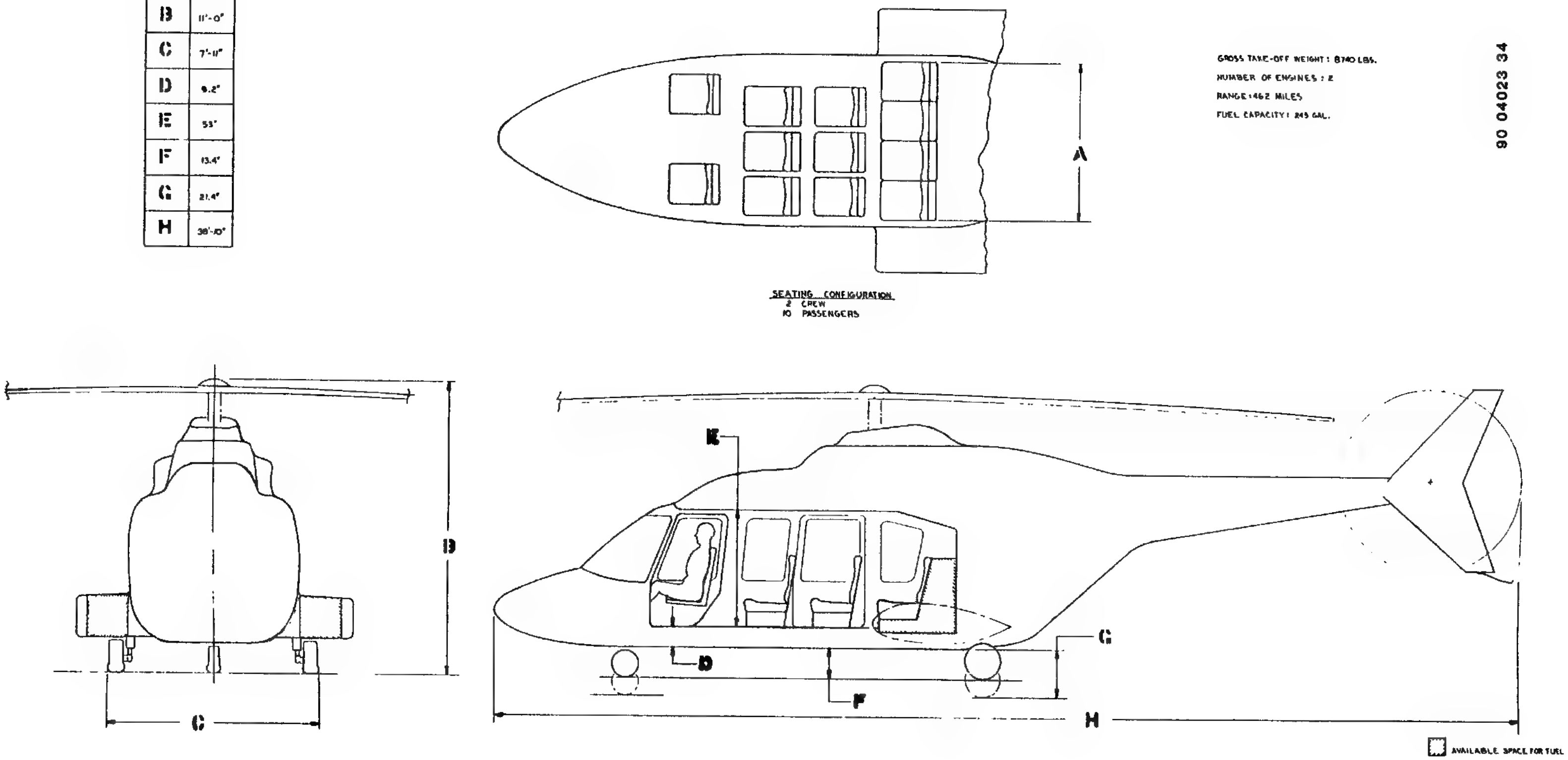

Figure 17.
Overall configuration and dimensions of the generic medium rotorcraft.

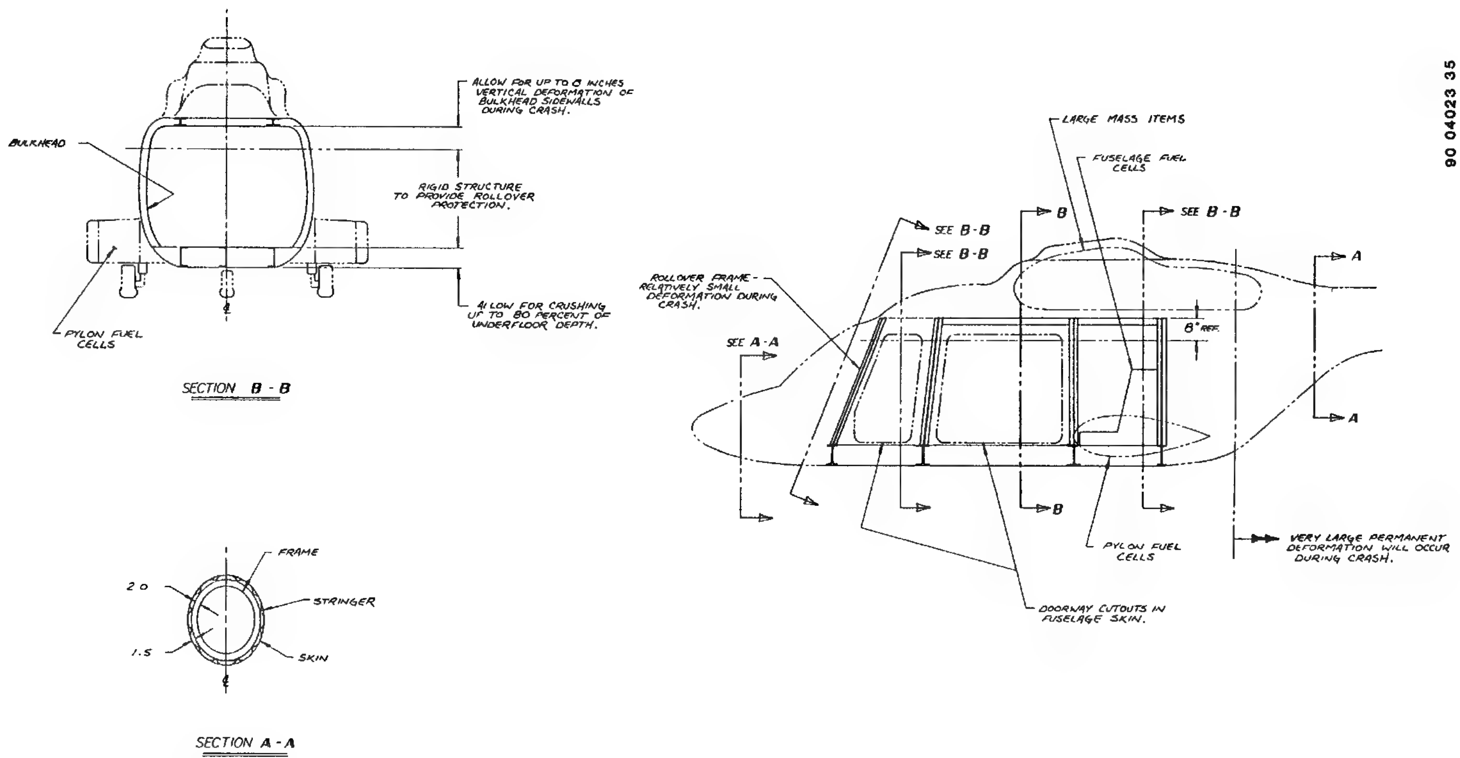

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Figure 18.
Structural details for the generic medium rotorcraft.

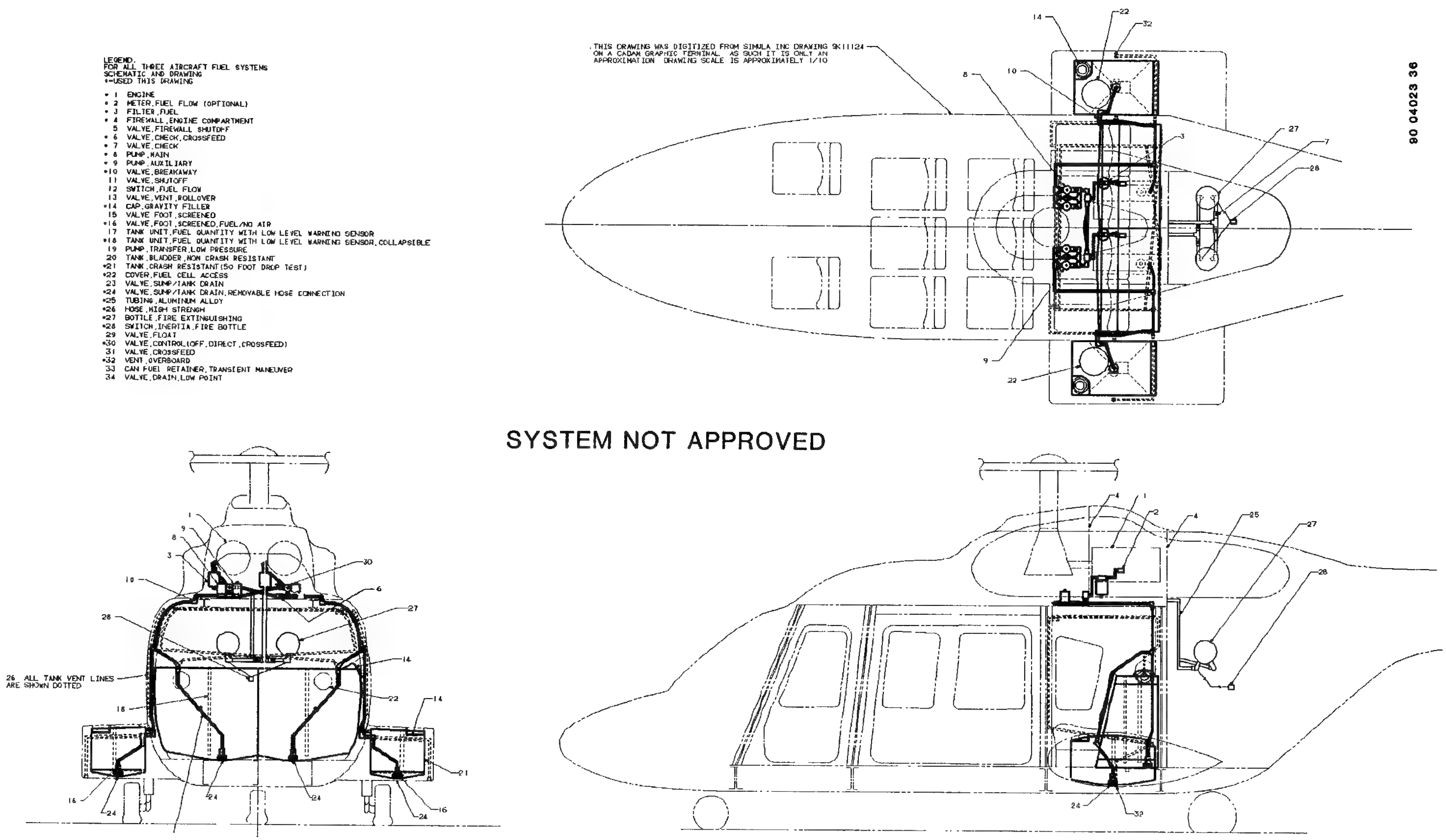
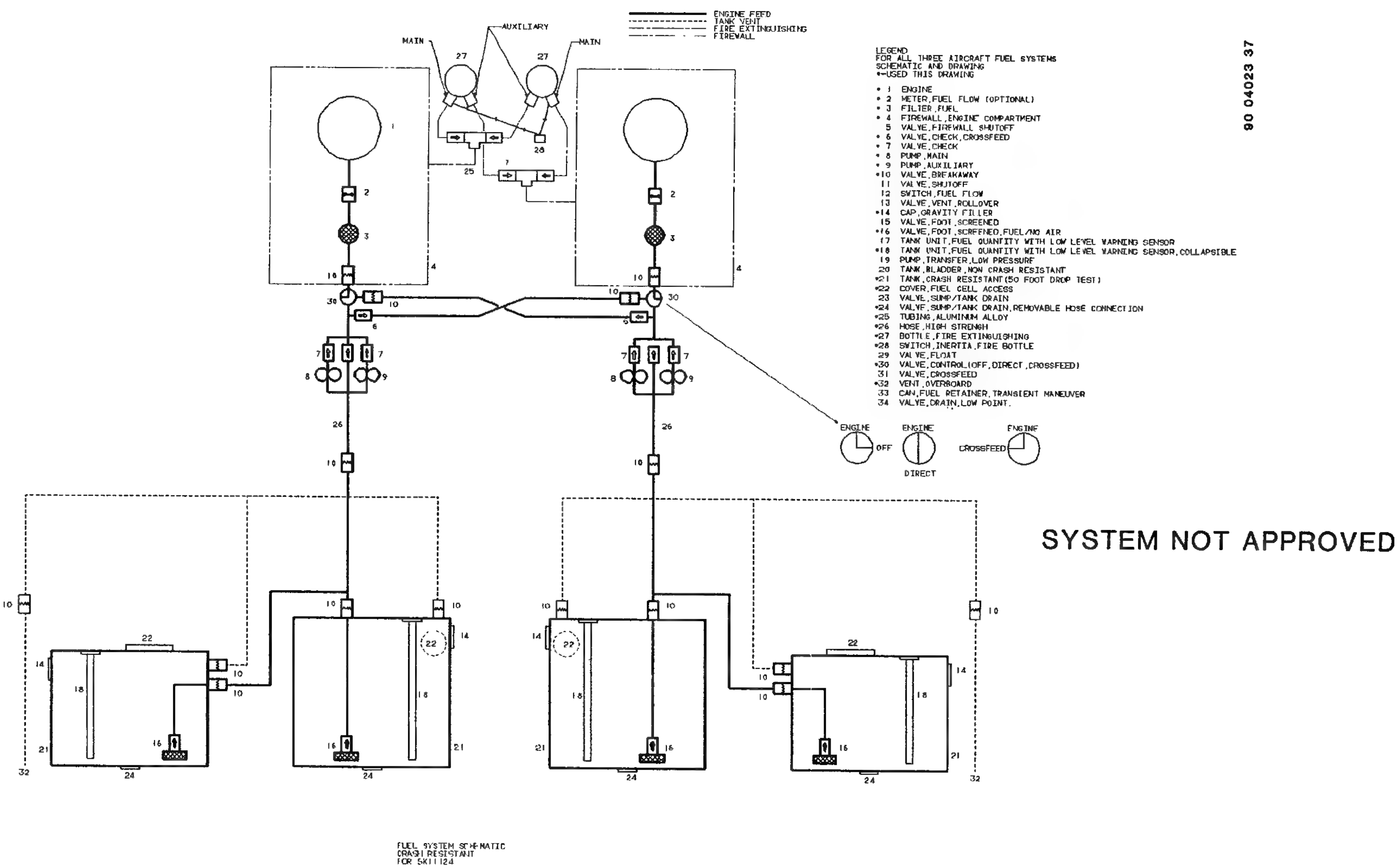
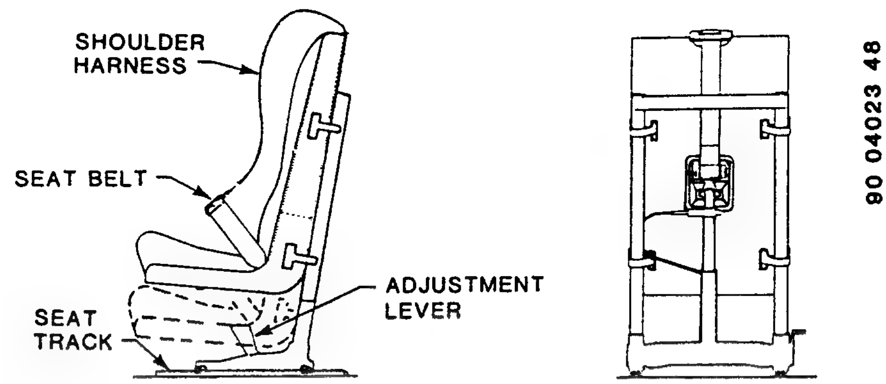


Figure 19.
Fuel system configuration for the generic medium rotorcraft.

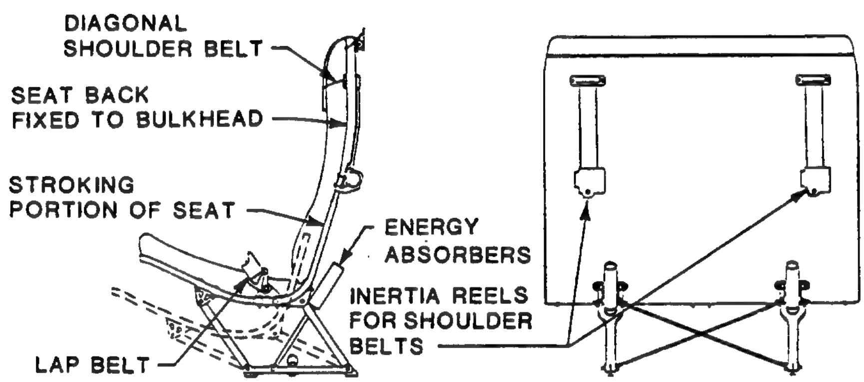


SYSTEM NOT APPROVED

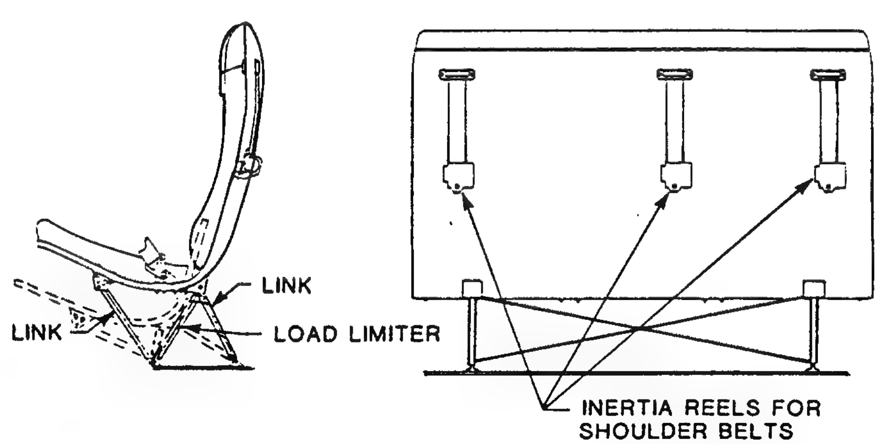
Figure 20.
Schematic diagram of the fuel system for the generic medium rotorcraft.



(a) Energy-absorbing crewseat (with vertical and fore/aft adjustment)



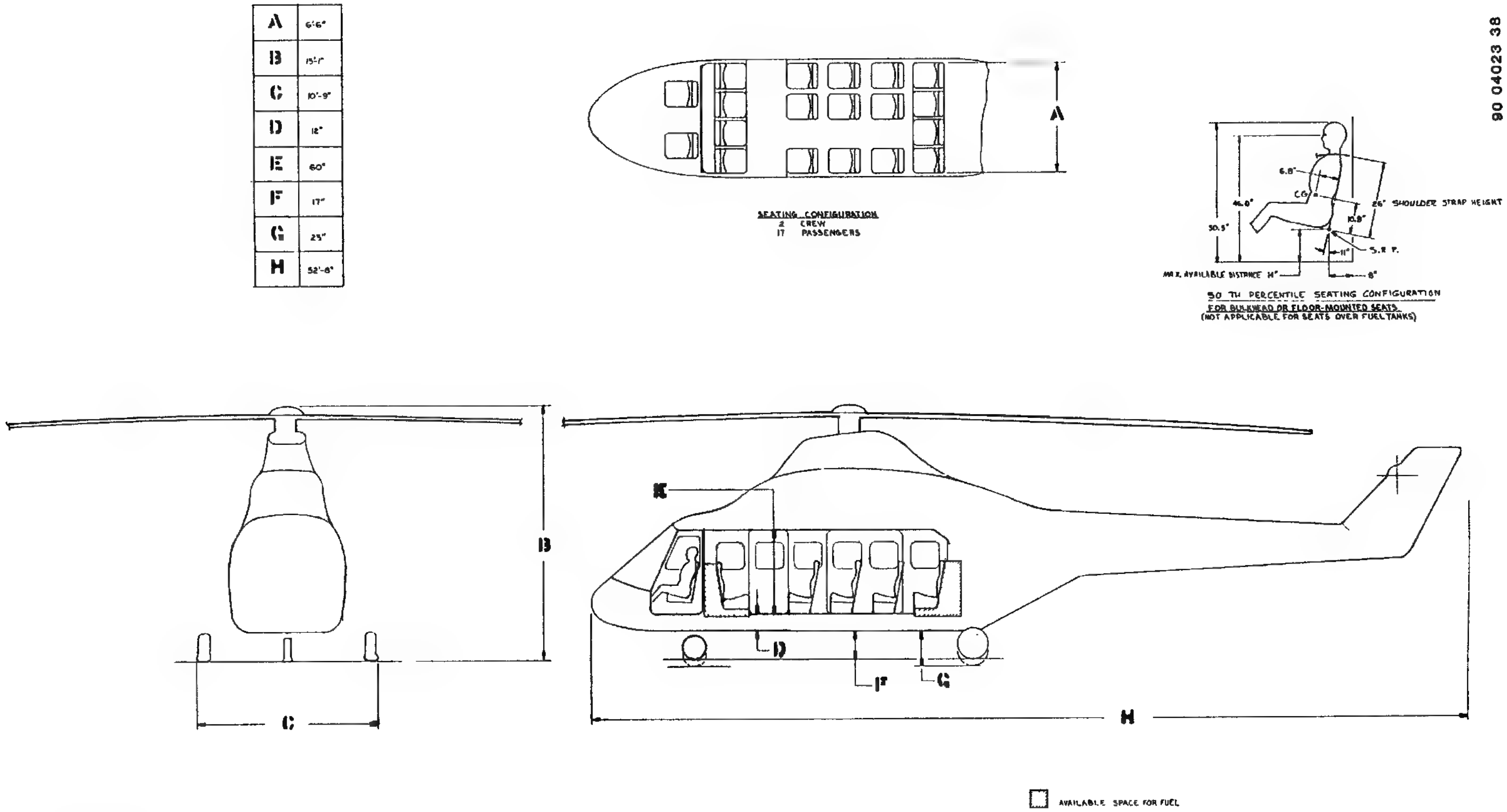
(b) Two-place passenger seat with combined floor and bulkhead mounting.



(c) Three-place, free-standing passenger seat.

Figure 21.
Seat concepts for the generic medium rotorcraft.

A	6'6"
B	15'-1"
C	10'-9"
D	12"
E	60"
F	17"
G	25"
H	52'-6"



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MAX GROSS TAKE-OFF WEIGHT : 16,200 LBS.
NUMBER OF ENGINES : 2
RANGE : 415 MILES
FUEL CAPACITY: 380 GAL.

Figure 22.
Overall configuration and dimensions of the generic heavy rotorcraft.

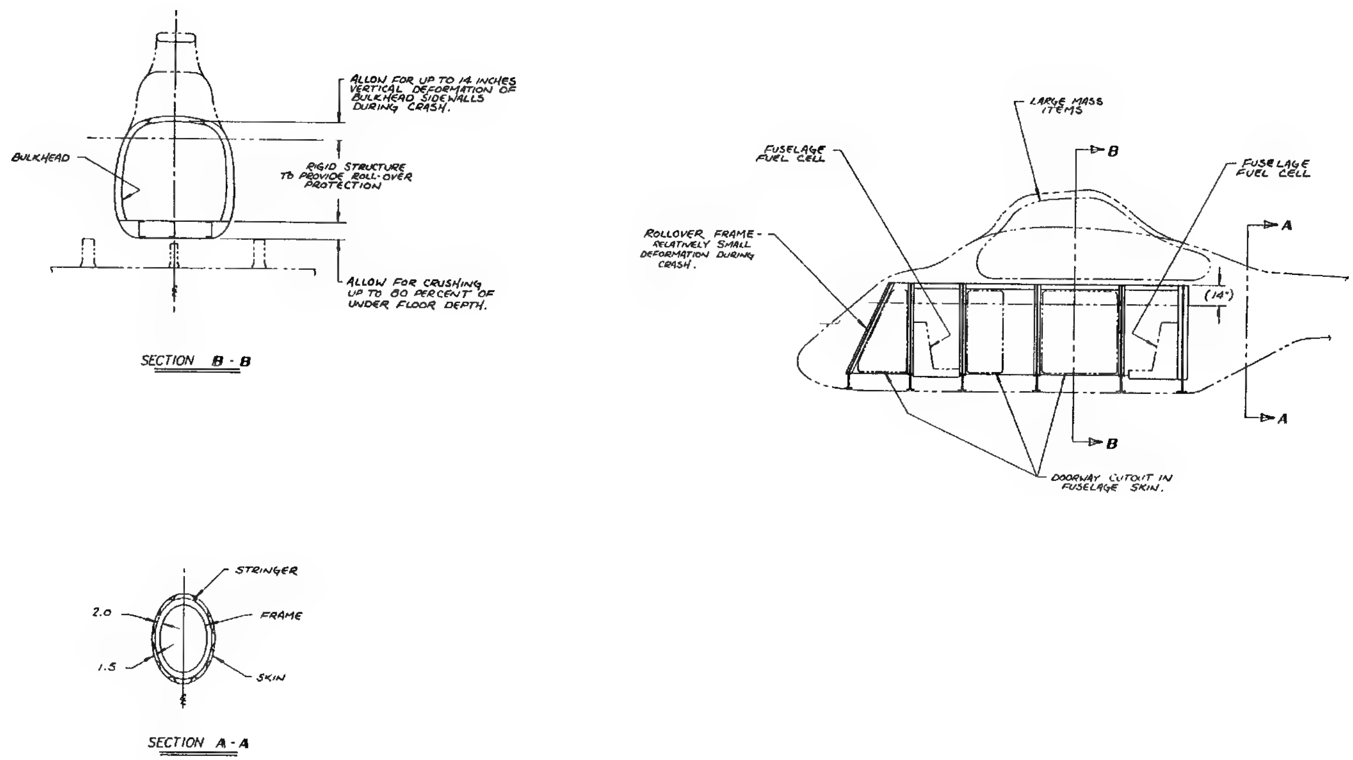

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Figure 23.
Structural details for the generic heavy rotorcraft.

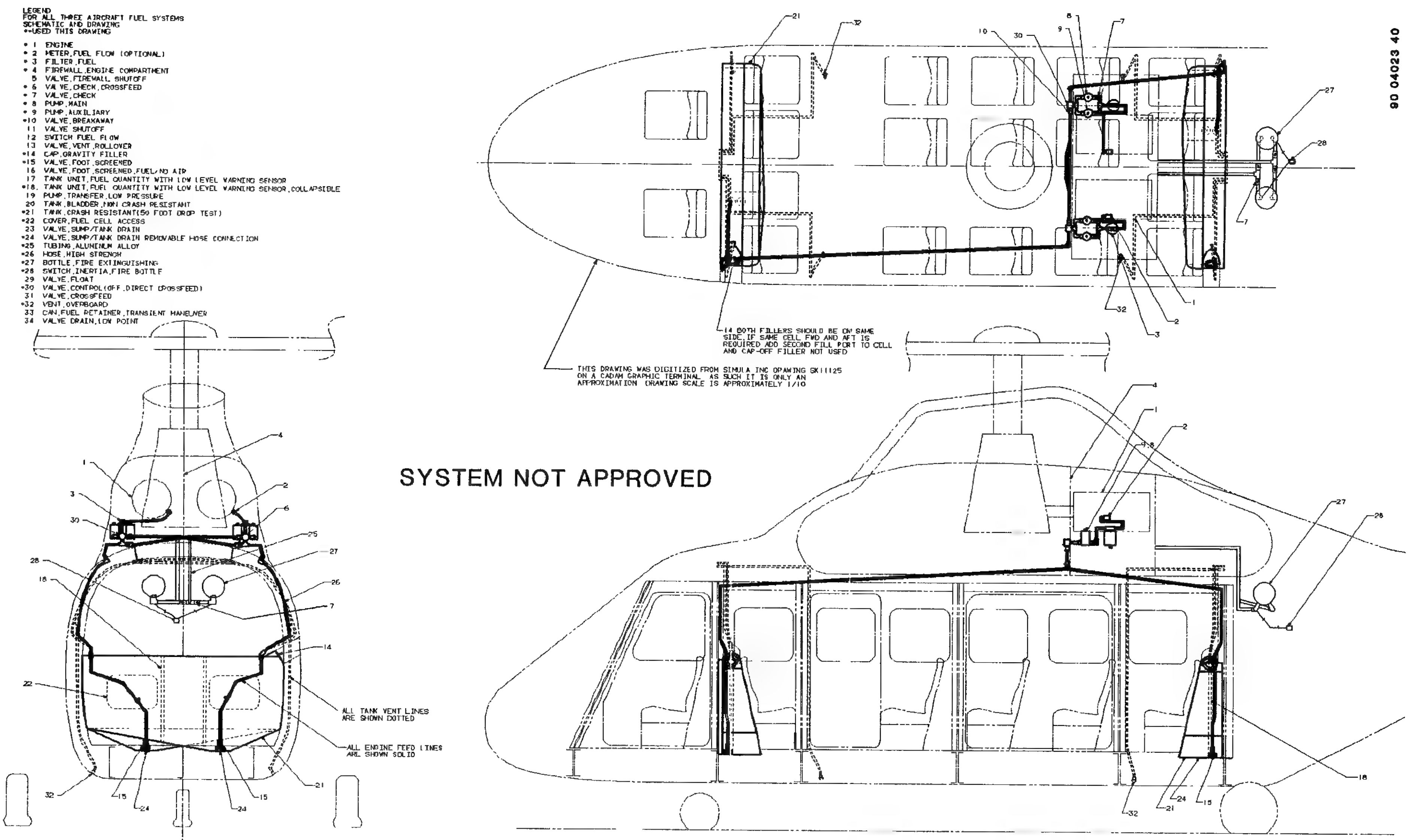
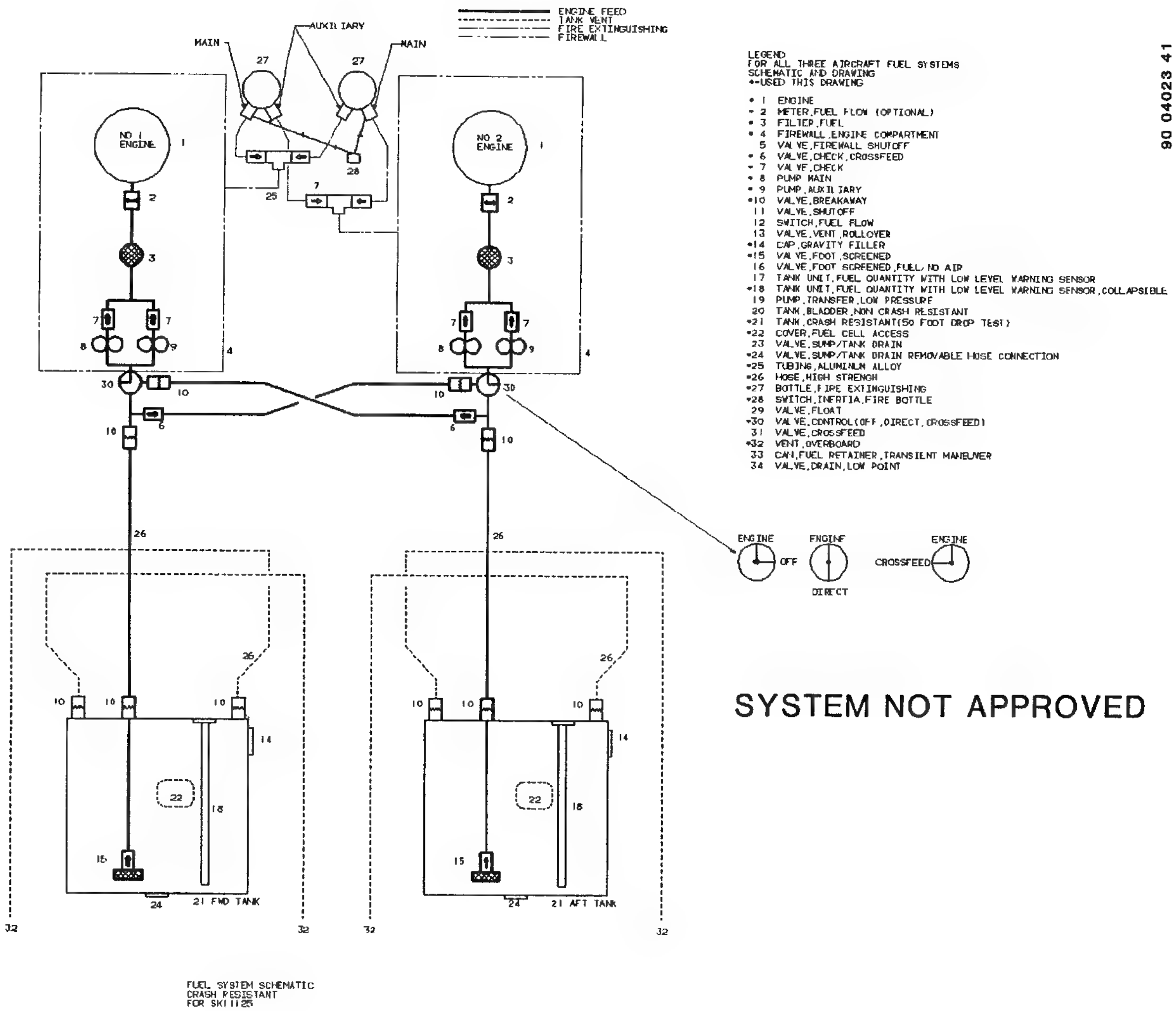
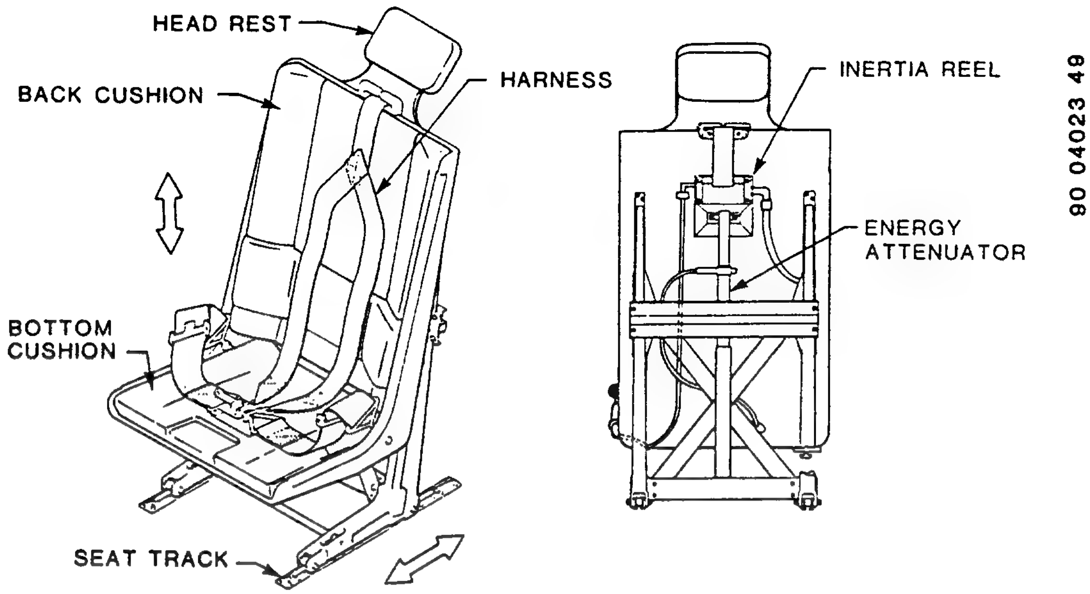


Figure 24.
Fuel system configuration for the generic heavy rotorcraft.

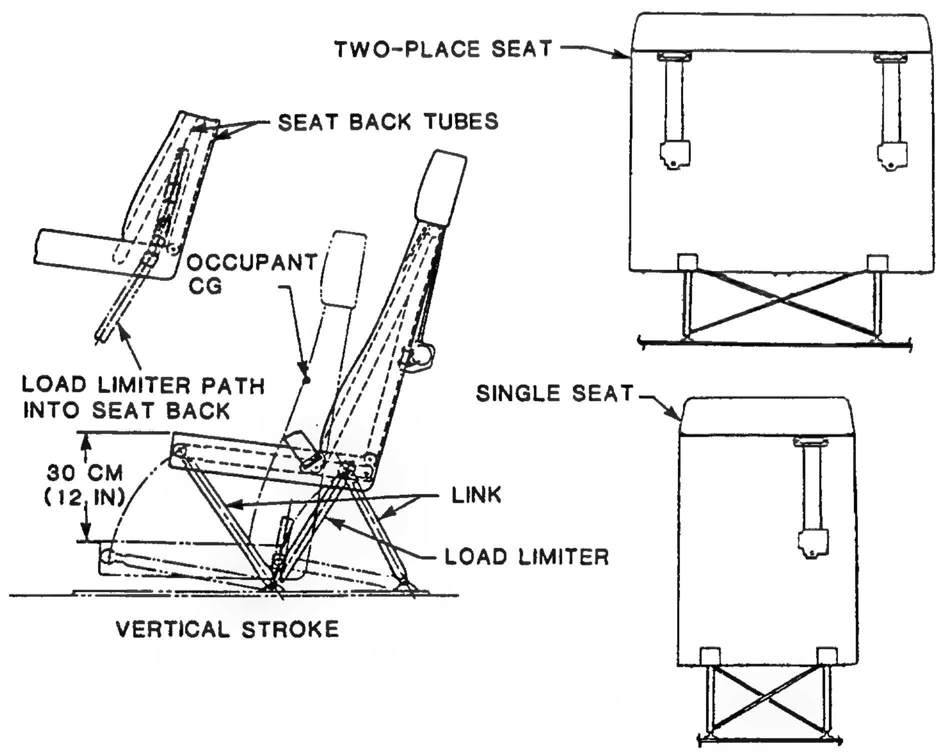


SYSTEM NOT APPROVED

Figure 25.
Schematic diagram of the fuel system for the generic heavy rotorcraft.



(a) Energy-absorbing crewseat (with vertical and fore/aft adjustment).



(b) Single and two-place passenger seats with energy absorption.

Figure 26.
Seat concepts for the generic heavy rotorcraft.

5.0 CRASH RESISTANCE TRADE-OFF ANALYSIS

A detailed trade-off analysis was conducted to determine an appropriate level of crash resistance for civil rotorcraft. The analysis took into account the frequency and severity of accidents and associated injuries, as well as the effect of weight penalty on rotorcraft design to meet specific crash resistance levels. The analysis was conducted by weight class to determine trends with rotorcraft size.

5.1 ACCIDENT AND INJURY SEVERITY ANALYSIS

An extensive evaluation of civil rotorcraft accidents was conducted in the study described in Reference 1. In that study, a sample of 311 accident cases was examined out of a total of 1,351 accidents occurring during the five-year period from January 1974 to December 1978. An overview of the sets of accidents examined in this study is shown in Figure 27. Reference 1 contains a detailed evaluation of the trends found in these 311 civil rotorcraft accidents.

From the 311 accident samples, the aircraft impact velocity and the potential level of survivability in 132 cases could be determined. The aircraft impact velocity was defined by the vertical, longitudinal, and lateral velocity components in the aircraft coordinate system. The level of survivability was identified by three categories: survivable, partially survivable, and nonsurvivable. Accidents were judged to be survivable or partially survivable according to the following definitions:

- Survivable - The acceleration environment was within the limits of human tolerance, and a sufficient occupiable volume remained for properly restrained (lap belt and shoulder harness) occupants. The hazards associated with postcrash fire were not considered as a factor in determining occupant survivability.

- Partially Survivable - Some portion of the cockpit or cabin met the definition of survivable.

Figure 28 shows the distribution of the 132 accidents plotted by the two predominate velocity components: vertical and longitudinal. It was found in the study that the lateral velocity component was of lesser significance in determining the severity of the accident and magnitude of occupant injuries.

Examination of the data in Figure 28 shows the expected trend of increasingly less survivable conditions in the aircraft as the impact velocity increases. Generally, the higher the vertical velocity, the greater chance that the crash would be nonsurvivable. The data imply that nonsurvivable conditions occur in impacts with vertical velocities of 30 ft/sec or more. Therefore, it might be concluded that the vertical velocity level of 30 ft/sec represents the upper bound for the current rotorcraft fleet. The correlation between longitudinal impact velocity and survivability is not as strong as that for vertical impact velocity.

The relationship between occupant injury and impact velocity was also examined. Out of the 132 accidents with known impact velocities and survivability, there was sufficient information to determine the level of injury for 116 occupants. Figure 29 shows the injury severity plotted as a function of vertical and longitudinal impact velocity for the aircraft. Again, there is a definite trend of more serious injury with increasing impact velocity. This trend appears to hold for both

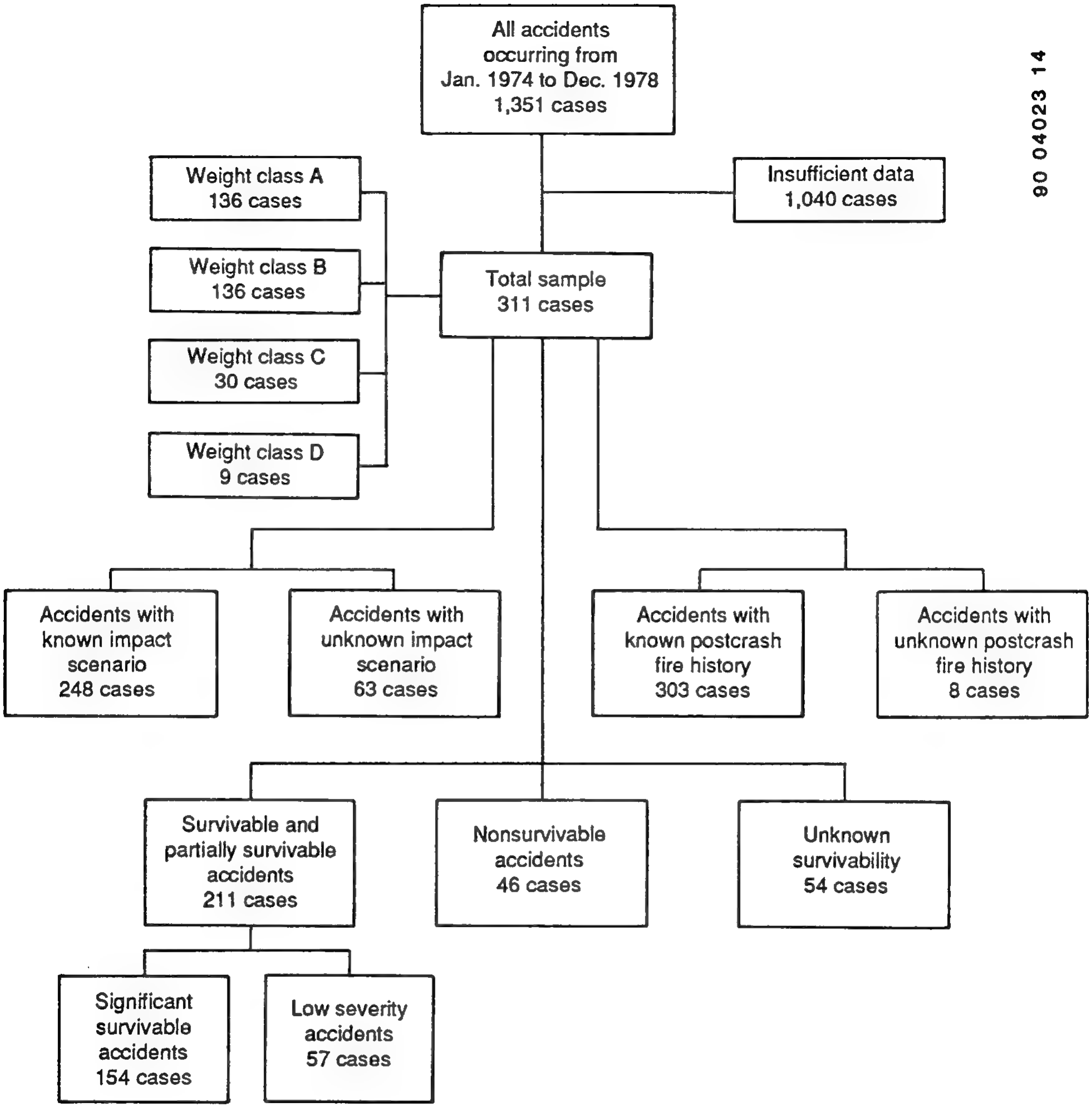


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Figure 27.
Overview of rotorcraft accident evaluation sample from Reference 1.

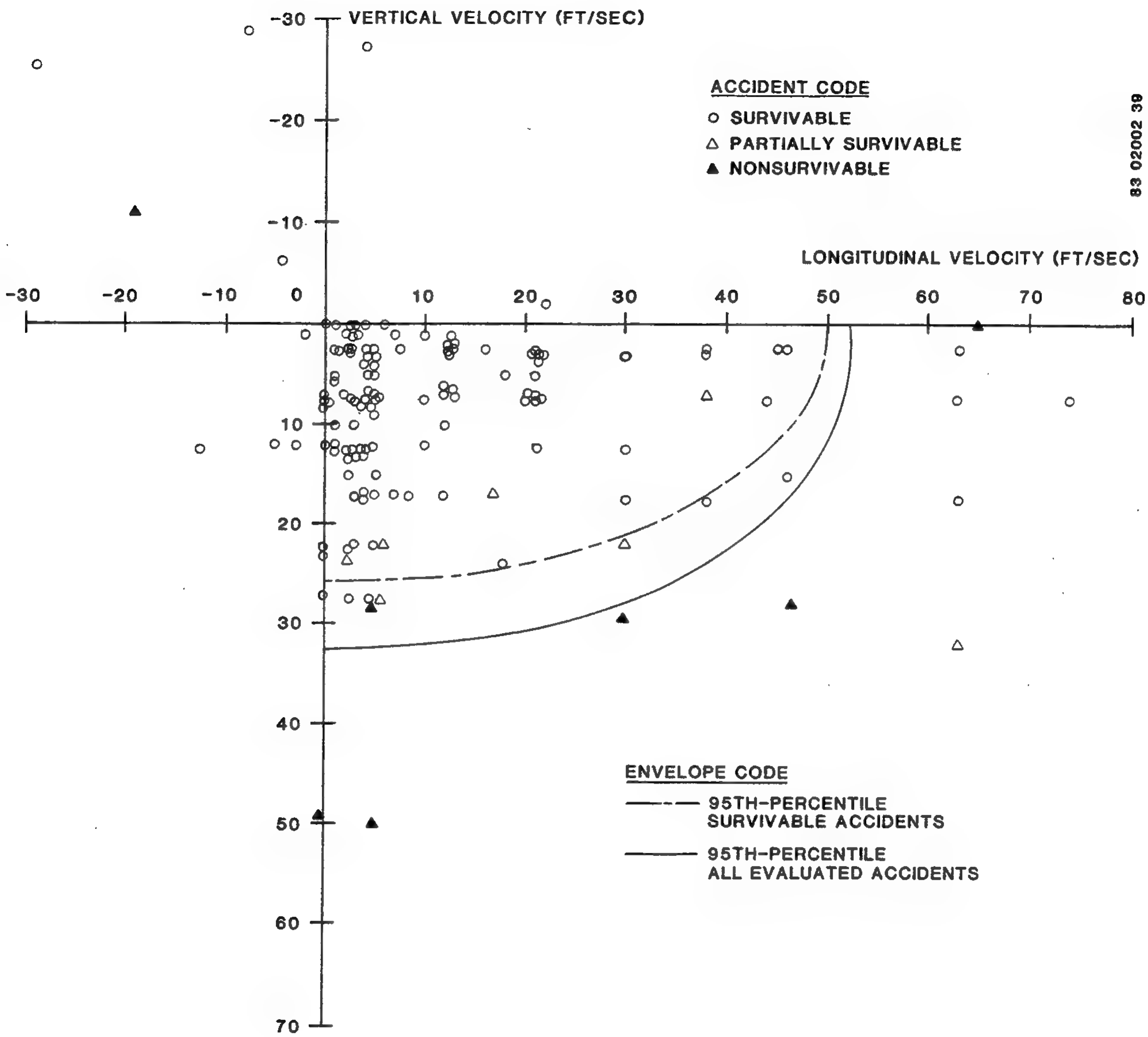


Figure 28.
Accident survivability distribution as a function of impact velocity.

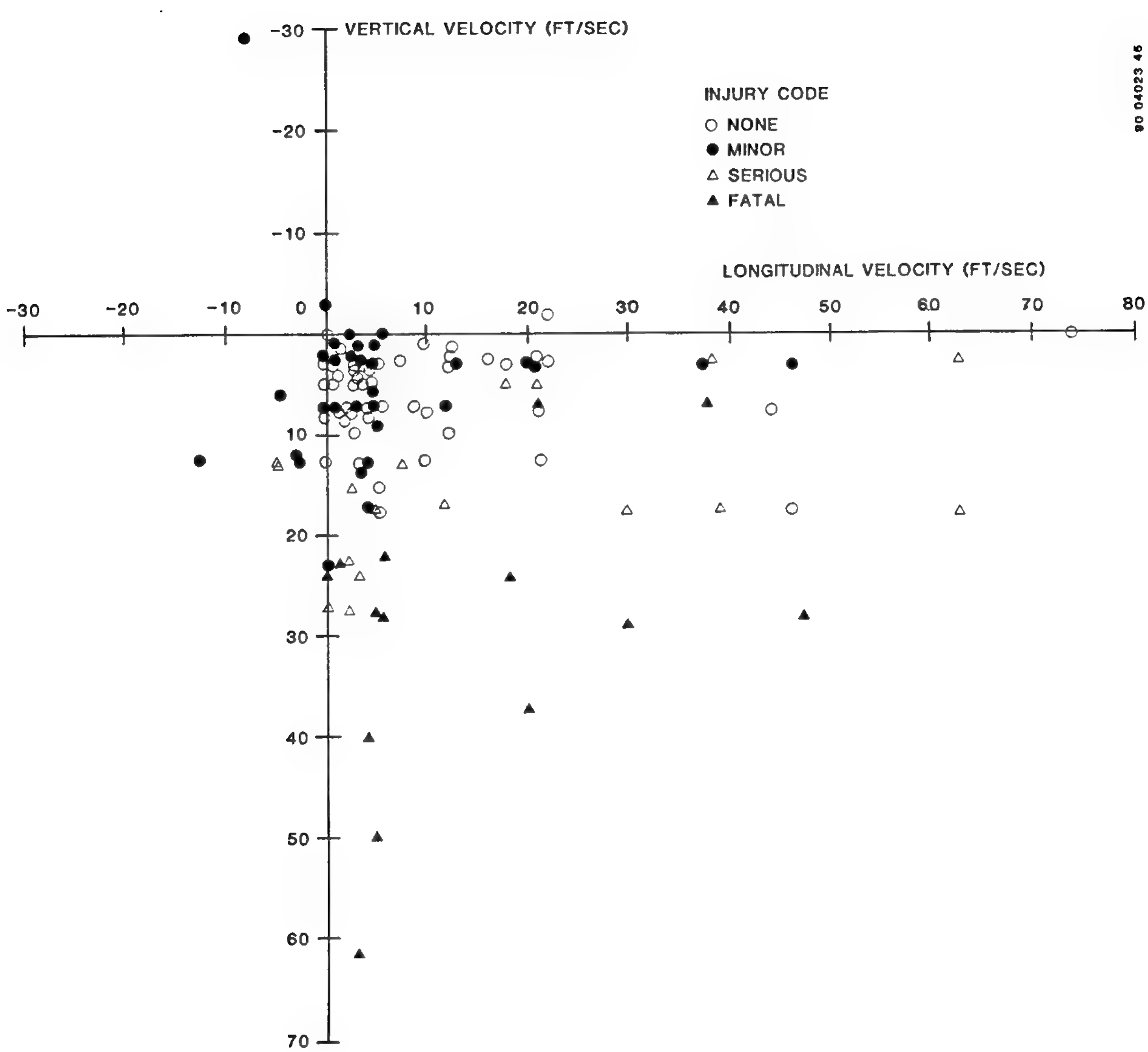


Figure 29.
Injury severity distribution as a function of impact velocity.

vertical and longitudinal impact velocity. To quantify these trends, the injury severity distribution plot was broken into six levels based on the magnitude of the vertical and longitudinal velocity. Figure 30 shows the six levels plotted over the injury severity distribution. A summary of the number of injuries found within each of the six impact levels is presented in Table 15.

Analysis of the injury data in Table 15 verifies the trend of increasing injury severity with increasing impact velocity from this sample of known injuries. To further quantify the influence of impact velocity on injury severity, the data were examined by using weighting factors based on injury severity and on relative injury cost. The first correlation is shown in Table 16. This correlation is based on the accumulated Abbreviated Injury Scale (AIS) score approach used in Reference 1. The accumulated AIS score is the summation of the number of persons receiving an injury times the average abbreviated injury score for the severity category (Reference 86).

Since the sample size of known injuries was small, the actual magnitude of the accumulated AIS score has little significance. However, the trend of accumulated AIS scores with impact level is significant. The final column in Table 16 shows the percentage of accumulated AIS scores occurring in each of the six impact levels. The significant trend is the relatively constant percentage that occurs in impact levels 1 through 4. Impact level 5 shows a major increase, while level 6 shows a drop. This would indicate that a significant number of severe injuries occur in impact level 5.

A second correlation was developed using cost as a weighting factor for the number of injuries occurring in each impact level. The injury costs used here were established by the FAA for use in cost/benefit analyses. The values include both medical costs and court settlements. The magnitude of the established costs was $1.5 million, $640,000, and $2,300 for fatal, serious, and minor injuries, respectively. If a passenger was uninjured, then an injury cost of zero was used. The injury severity correlation weighted by these costs is shown in Table 17.

The data contained in Table 17 show a relationship between cost of injuries and impact levels. The costs associated with impact levels 1 through 4 are relatively small compared with those found in impact level 5. Approximately one-third of all injury costs occur in accidents falling in impact level 5. The costs in impact level 6 are also high, although lower than level 5. The trends found in the cost-weighted correlation are very similar to those found in the injury-severity-weighted correlation shown in Table 16.

The analyses presented in this section reveal that a significant percentage of the major injuries to passengers and the costs associated with these injuries occur in impact level 5. The upper bound of this impact level represents the 95th-percentile significant survivable impact conditions defined in Reference 1 for U.S. civil rotorcraft. It appears that design and test criteria for civil rotorcraft should consider protection to the associated impact velocity levels of 26 ft/sec vertical and 50 ft/sec longitudinal. Approximately 84 percent of all persons involved in rotorcraft accidents would fall within these designated levels.

5.2 CRASH TOLERANCE WEIGHT PENALTY ANALYSIS

Whereas the accident and injury severity analysis presented in Section 5.1 evaluated appropriate levels of crash resistance to protect the U.S. civil flying population, this section describes the weight penalties associated with achieving various levels of crash protection. The weight penalty analysis was a major portion of the overall study, resulting in extensive documentation.

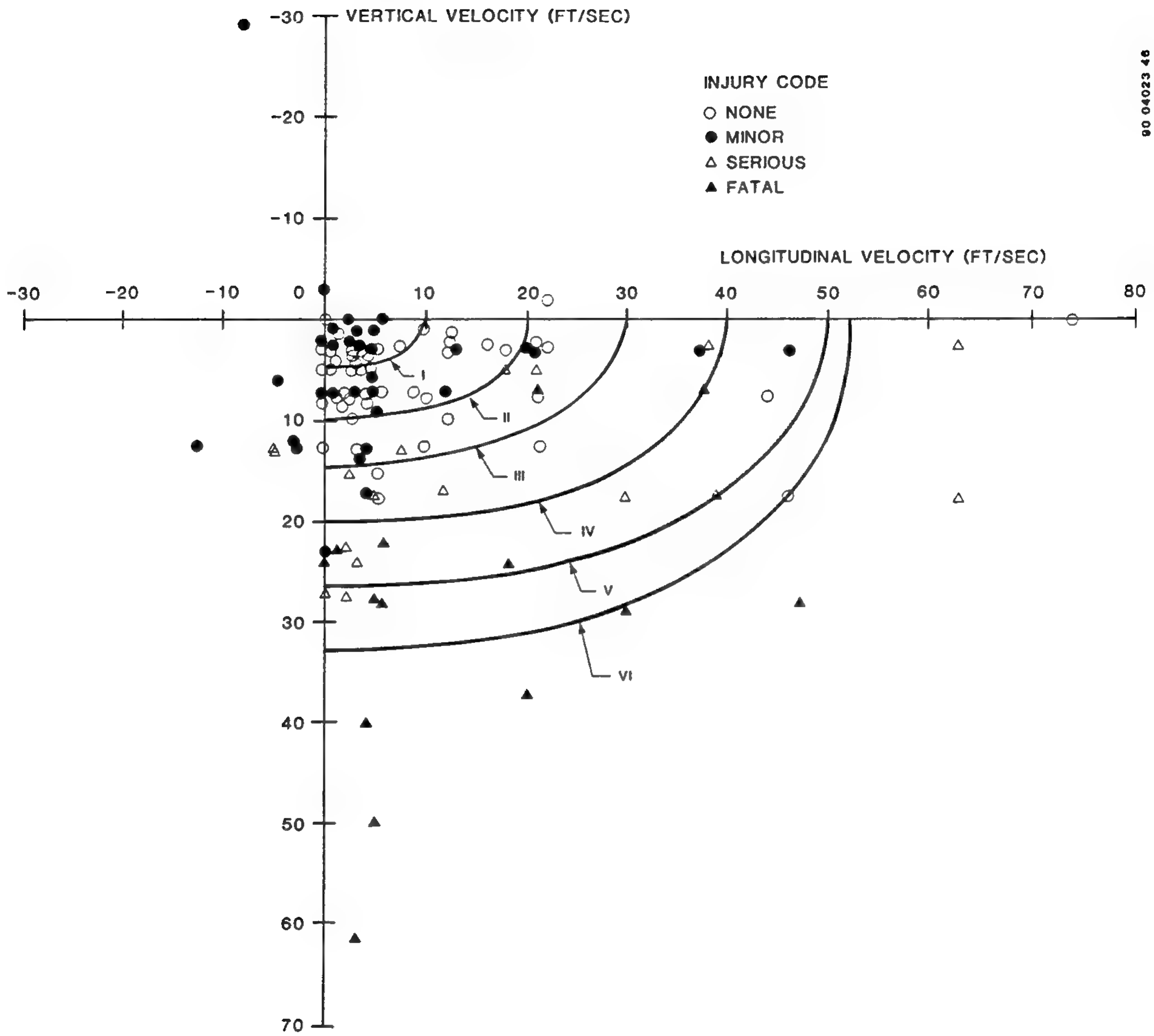


Figure 30.
Identification of the six impact levels.

Table 15.
Summary of injury severity data as a function of six impact levels defined in Figure 30

Impact Level	Vertical Velocity		Longitudinal Velocity		Number of Persons Receiving Injuries of this Severity					% of Total Persons
	ft/sec	Percentile(2)	ft/sec	Percentile(2)	None	Minor	Serious	Fatal	Total	
1	5	41	10	68	18	11	0	0	29	25.0
2	10	63	20	82	21	9	1	0	31	26.7
3	15	79	30	87	9	4	2	1	16	13.8
4	20	88	40	92	3	2	4	0	9	7.8
5	26	95	50	95	1	2	4	5	12	10.3
6	32	95 (3)	52	95 (3)	1	0	2	3	6	5.2
All Other(1)					0	5	3	5	13	11.2
									116	100.0

NOTES

(1) The category of "all other" takes into account accidents at velocity levels exceeding impact level 6 and other miscellaneous types of accidents such as inverted impact, wire strikes, etc.

(2) This is the percentile of cumulative frequency of occurrence for survivable accidents occurring at, or below, this velocity level.

(3) The percentile for level 6 is the 95th-percentile for all civil rotorcraft accidents (survivable, partially survivable, and nonsurvivable).

Table 16.
Correlation between impact level and accumulated AIS score

Impact Level	Accumulated AIS Score — No. of Persons X Average AIS Score: None (AIS=0)	Minor (AIS=1)	Serious (AIS=3)	Fatal (AIS=5)	Total Score	% of Total Score
1	0	11	0	0	11	7.3
2	0	9	3	0	12	8.0
3	0	4	6	5	15	9.9
4	0	2	12	0	14	9.3
5	0	2	12	25	39	25.8
6	0	0	6	15	21	13.9
All Other	0	5	9	25	39	25.8
					151	100.0

Table 17.
Correlation between impact level and total injury cost

Impact Level	Injury Cost — No. of Persons X Average Injury Cost: None ($0 ea.)	Minor ($2,300 ea.)	Serious ($640,000 ea.)	Fatal ($1.5 million)	Total Cost	% of Total Cost
1	0	25,300	0	0	25,300	0.1
2	0	20,700	640,000	0	660,700	2.1
3	0	9,200	1,280,000	1,500,000	2,789,200	8.9
4	0	4,600	2,560,000	0	2,564,600	8.2
5	0	4,600	2,560,000	7,500,000	10,064,600	32.1
6	0	0	1,280,000	4,500,000	5,780,000	18.5
All Other	0	11,500	1,920,000	7,500,000	9,431,500	30.1
Total					31,315,900	100.0

Summaries of the weight penalty analyses for fuselage structure and landing gear, fuel systems, and seating systems are presented in Appendices A, B, and C, respectively. This section presents only the approach to the weight penalty analysis and summarizes the overall results.

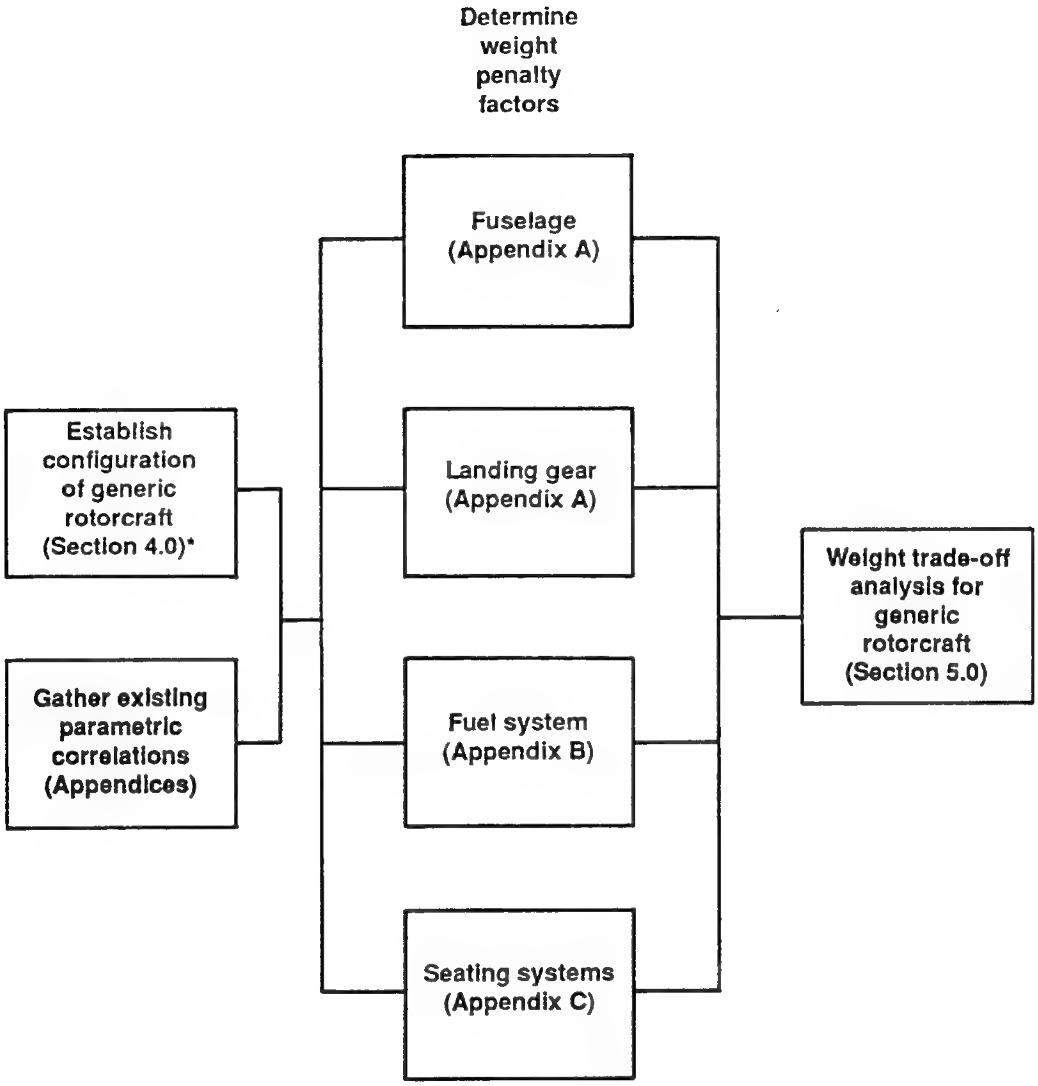
The weight penalty analysis was based on existing parametric correlations relating weight penalty for various components or structural features to a defined property of the aircraft such as design gross weight. Weight penalty correlations were examined for each of the four major systems which contribute to crash resistance: fuselage, landing gear, fuel system, and seating system. Within each of these four aircraft systems, the weight penalty calculation took into account various subfactors related to the specific configuration of the aircraft. The configuration of each of the three generic aircraft was used to determine a detailed weight penalty for achieving specific levels of crash resistance.

Figure 31 shows the approach used in the weight penalty analysis. The initial steps were to define rotorcraft configuration and to gather validated parametric correlations. Then, weight penalty factors were determined for each of the major systems at several levels of crash resistance. The final step was to assemble the overall weight penalty for the aircraft. Trade-offs in the amount of crash energy to be handled by each system were considered. The goal of the trade-offs was to achieve a balanced energy management system with a minimum weight.

In calculating the weight penalty factors, five levels of crash resistance were identified for evaluation. The five levels were based primarily on vertical impact velocity since vertical impact velocity was found to be the primary factor influencing occupant survivability. The five vertical impact velocities considered were 10 ft/sec, 14 ft/sec, 20 ft/sec, 26 ft/sec, and 32 ft/sec. The lowest velocity, 10 ft/sec, was selected because it represents a baseline design corresponding to the current requirements contained in FAR Part 27. The two highest velocities, 26 ft/sec and 32 ft/sec, were the 95th-percentile of survivable accident level and 95th-percentile of all accidents, respectively, from the Reference 1 study of civil rotorcraft. The other two velocities, 14 ft/sec and 20 ft/sec, were selected as intermediate values in which parametric data existed.

The outcome of the weight penalty analysis was a series of weight penalties for each generic rotorcraft at the five selected vertical impact velocities. These weight penalties are listed in Table 18. The weight penalties are shown in terms of a percentage of DGW and total weight penalty in pounds.

Several points can be made about the data in Table 18. The fuselage, landing gear, and seating systems will have a zero percent weight penalty at the baseline 10 ft/sec vertical impact velocity since they require no modification to meet this condition. However, fuel systems designed to meet a crash resistance requirement at 10 ft/sec would need additional features compared to those required to meet the current FAR's. Therefore, a small weight penalty is shown for fuel systems at this vertical impact velocity. The second point is that the weight penalty, as a percentage of gross weight, is higher for smaller size rotorcraft. This trend would imply that it is more difficult to incorporate crash resistance in smaller rotorcraft than in larger models. The final point from the data in Table 18 is that weight penalties of 3.57, 3.11, and 2.52 percent would be imposed on the generic rotorcraft representing weight classes B, C, and D, respectively, in order to meet the 95th-percentile survivable impact level (26 ft/sec) defined as optimum in the previous section. At this crash resistance level, a weight penalty of 146 lb, 272 lb, and 408 lb would be imposed on the light, medium, and heavy generic rotorcraft designs, respectively.



*Note in parenthesis is location in this report where supporting data can be found.

Figure 31.
Overall approach for weight penalty analysis.

Table 18. Summary of crash resistance weight penalty factors for the three generic rotorcraft						
Generic Type	Vertical Impact Velocity (ft/sec)	Weight Penalty Factors (Percent of DGW) Fuselage and Landing Gear	Fuel System	Seating System	Total Aircraft	Weight Penalty (lb)
Light DGW=4,100 lb	10	0.0	0.43	0.00	0.43	17.6
	14	0.2	0.46	0.38	1.04	42.6
	20	0.6	0.64	0.90	2.14	87.7
	26	1.1	0.96	1.51	3.57	146.4
	32	2.1	1.43	1.99	5.52	226.3
Medium DGW=8,740 lb	10	0.0	0.43	0.00	0.43	37.6
	14	0.1	0.45	0.40	0.95	83.0
	20	0.3	0.58	0.95	1.83	159.9
	26	0.7	0.82	1.59	3.11	271.8
	32	1.6	1.18	2.09	4.87	425.6
Heavy DGW=16,200 lb	10	0.0	0.22	0.00	0.22	35.6
	14	0.1	0.23	0.35	0.68	110.2
	20	0.2	0.30	0.83	1.33	215.5
	26	0.7	0.43	1.39	2.52	408.2
	32	1.2	0.62	1.83	3.65	591.3

The weight penalty factors shown in Table 18 were plotted so that trends could be examined. Figures 32, 33, and 34 are the graphical representations of the weight penalty factors as a function of vertical impact velocity for the three generic rotorcraft. The trend identified in Table 18, which shows the need for higher weight penalties to achieve specific crash resistance levels in smaller rotorcraft, was investigated further. Figure 35 shows the relationship between DGW and the level of crash resistance that can be achieved. As can be seen in Figure 35, at constant weight penalty factors, the crash resistance capability for the rotorcraft increases with increasing rotorcraft size.

5.3 CRASH RESISTANCE TRADE-OFF ANALYSIS

The trade-off analysis described here is the culmination of all the analytical studies performed for this program. A final trade-off analysis was conducted to arrive at a direct relationship between the frequency of occurrence of U.S. civil rotorcraft accidents and the weight penalty associated with providing crash resistance. This relationship was examined for various sizes of aircraft to determine if there was a size effect.

The initial step in the trade-off analysis was to define the ultralight weight class (representative of weight class A) consisting of two- to three-place rotorcraft such as the Bell 47, Robinson R-22, and Schweizer 269. A generic model representing this weight class would have a DGW of approximately 1,700 lb.

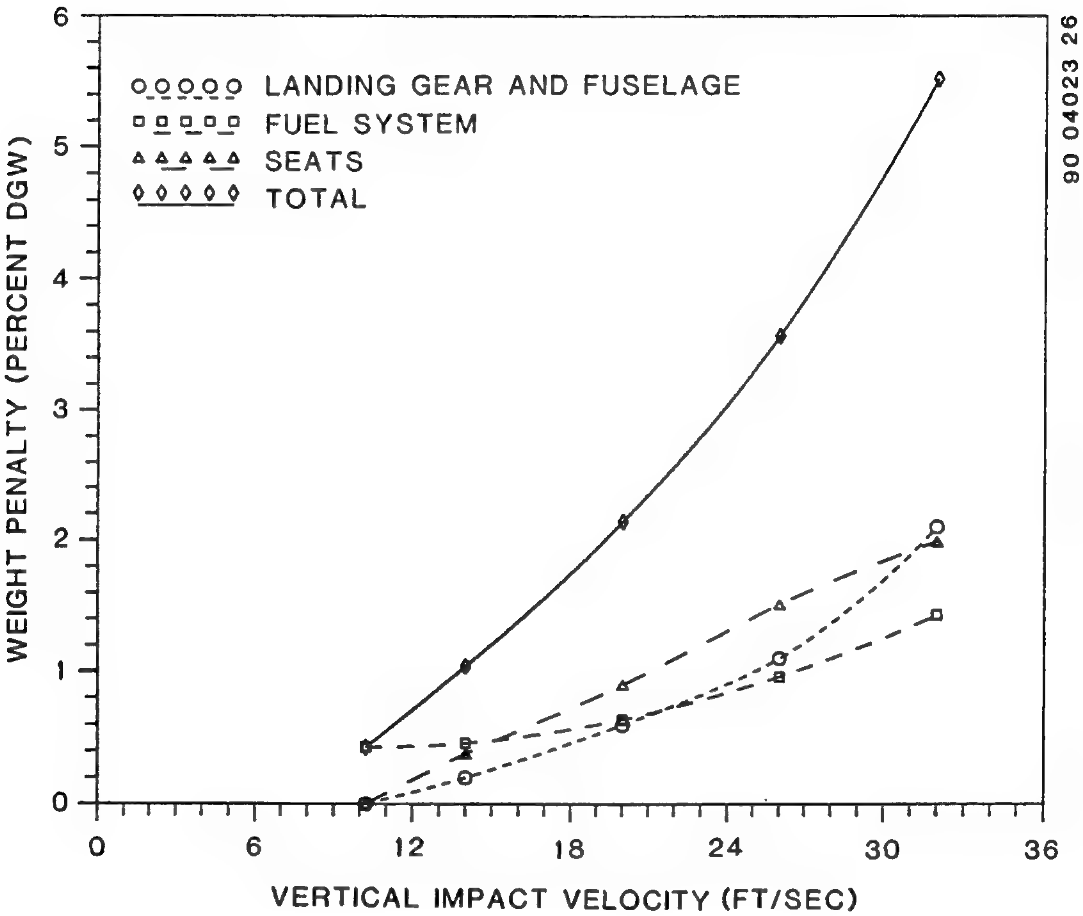


Figure 32.
Trends in weight penalty factors for the generic light rotorcraft.

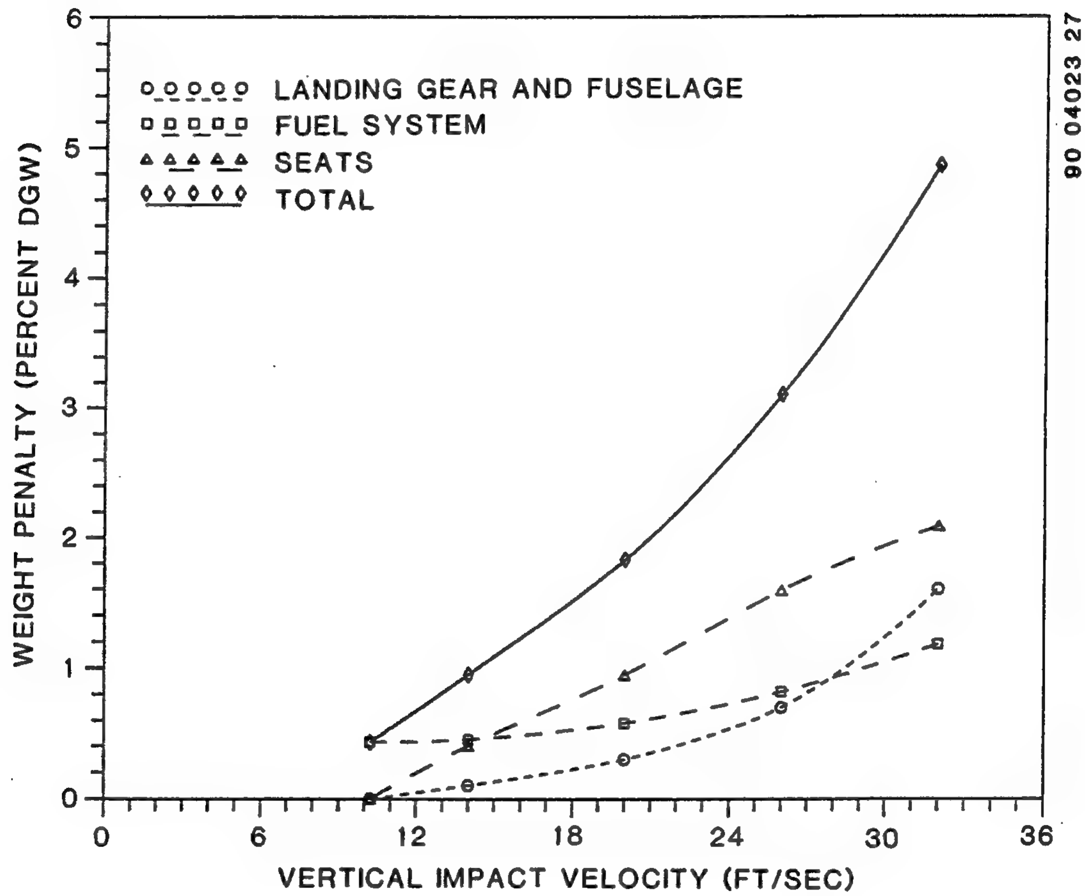


Figure 33.
Trends in weight penalty factors for the generic medium rotorcraft.

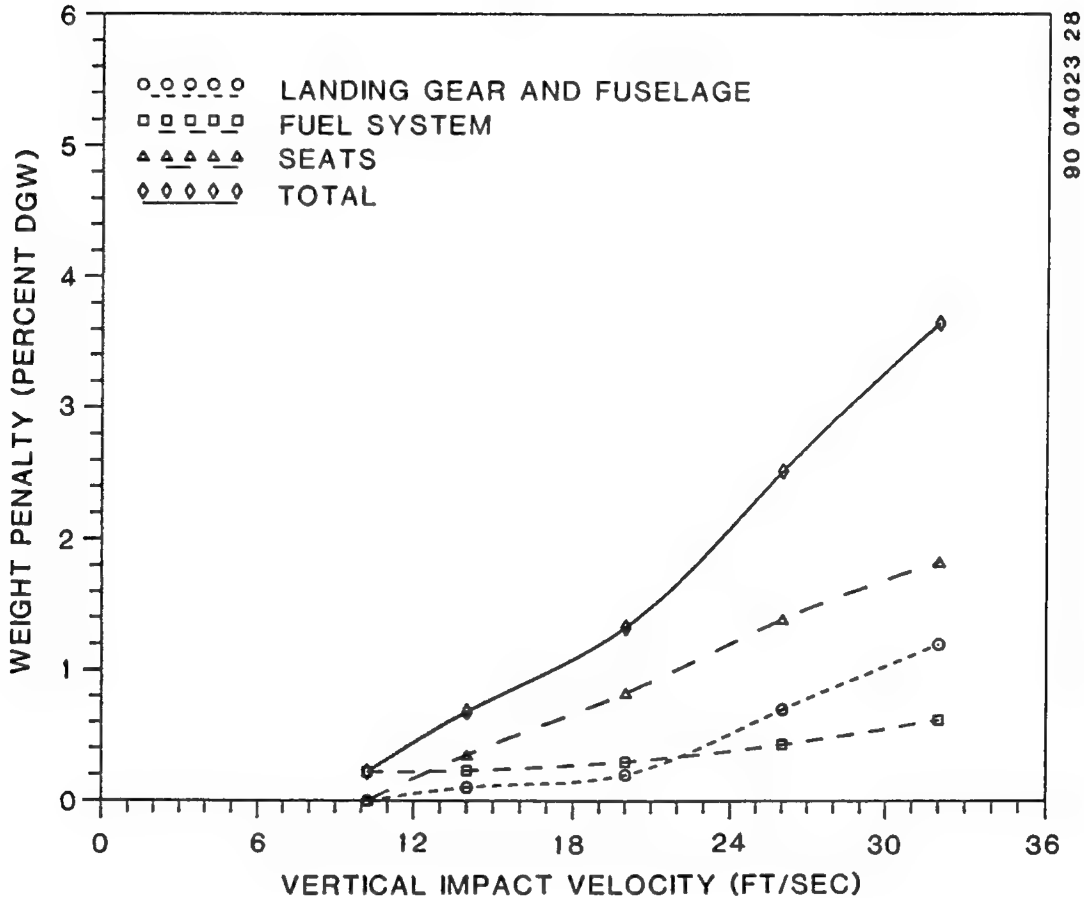


Figure 34.
Trends in weight penalty factors for the generic heavy rotorcraft.

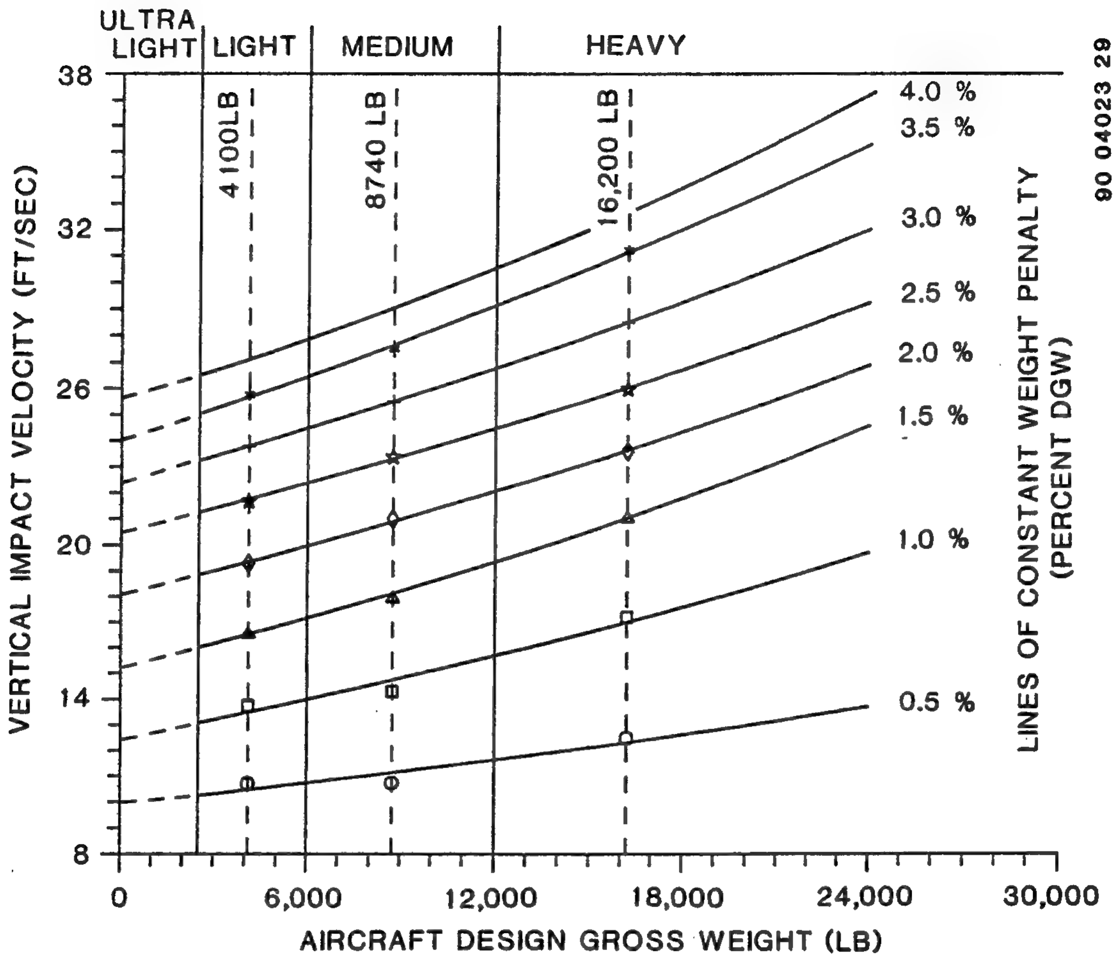


Figure 35.
Effect of design gross weight on crash resistance.

The second step in the analysis was to determine how frequently accidents occurred in each of the four weight classes at specific vertical impact velocities. Data from the Reference 1 study were used to determine the frequency of accidents in weight classes A and B. Accident frequency histograms for these weight classes are shown in Figures 36 and 37. The histograms are based on 89 accidents in weight class A and 87 accidents in weight class B. The frequency of occurrence of accidents in weight classes C and D were combined due to the small number of accidents available for evaluation. The combined frequency histogram for weight classes C and D is shown in Figure 38 and is based on 19 accidents.

The final step in the trade-off analysis was to develop the correlation between the accident frequency (by weight class) and the weight penalty. Figures 36, 37, and 38 provide the accident frequency as a function of vertical impact velocity. Figures 32, 33, and 34 from Section 5.2 give the weight penalty for weight classes B, C, and D as a function of vertical impact velocity. From the curves in Figure 35, the weight penalty for weight class A versus vertical velocity was extrapolated. Thus, the final step can be accomplished by correlating accident frequency and weight penalty using vertical impact velocity as the common denominator. The correlations developed through this process are shown in the Figures 39 through 42 for weight classes A, B, C, and D, respectively.

The data in Figures 39 through 42 can be interpreted as follows: given a specific weight penalty factor, the expected percent of accidents can be identified in which crash resistance would be provided. For example, it can be seen in Figure 39 that a weight penalty factor of 3.6 percent would coincide with a level of protection associated with the 95th-percentile vertical velocity for rotorcraft accidents in this weight class. If the four graphs for the individual weight classes are compared, it can be seen that the weight penalty factor to provide 95th-percentile vertical velocity coverage becomes smaller with increasing rotorcraft size. For weight classes A, B, C, and D the weight penalty factor is 3.6, 3.3, 2.9, and 2.4 percent, respectively. This trend is shown graphically in Figure 43. Although the weight penalty factor reduces with increasing rotorcraft size, Figure 43 shows that the actual weight penalty in pounds increases with size. To achieve the 95th-percentile crash resistance level, the typical rotorcraft in weight classes A, B, C, and D would experience weight penalties of 61, 137, 254, and 389 lb, respectively.

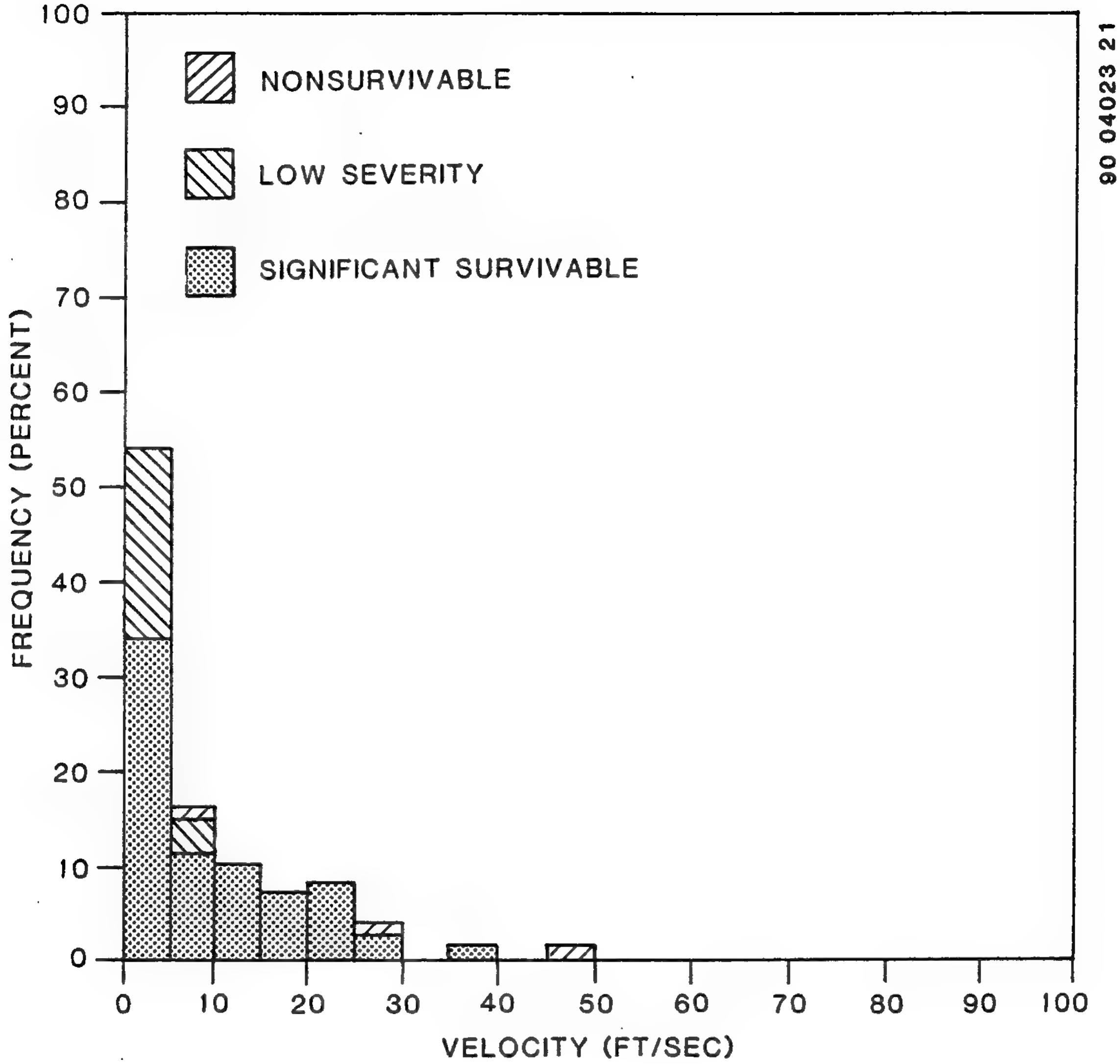


Figure 36.
Frequency of occurrence of vertical impact velocity, weight class A (89 accidents).

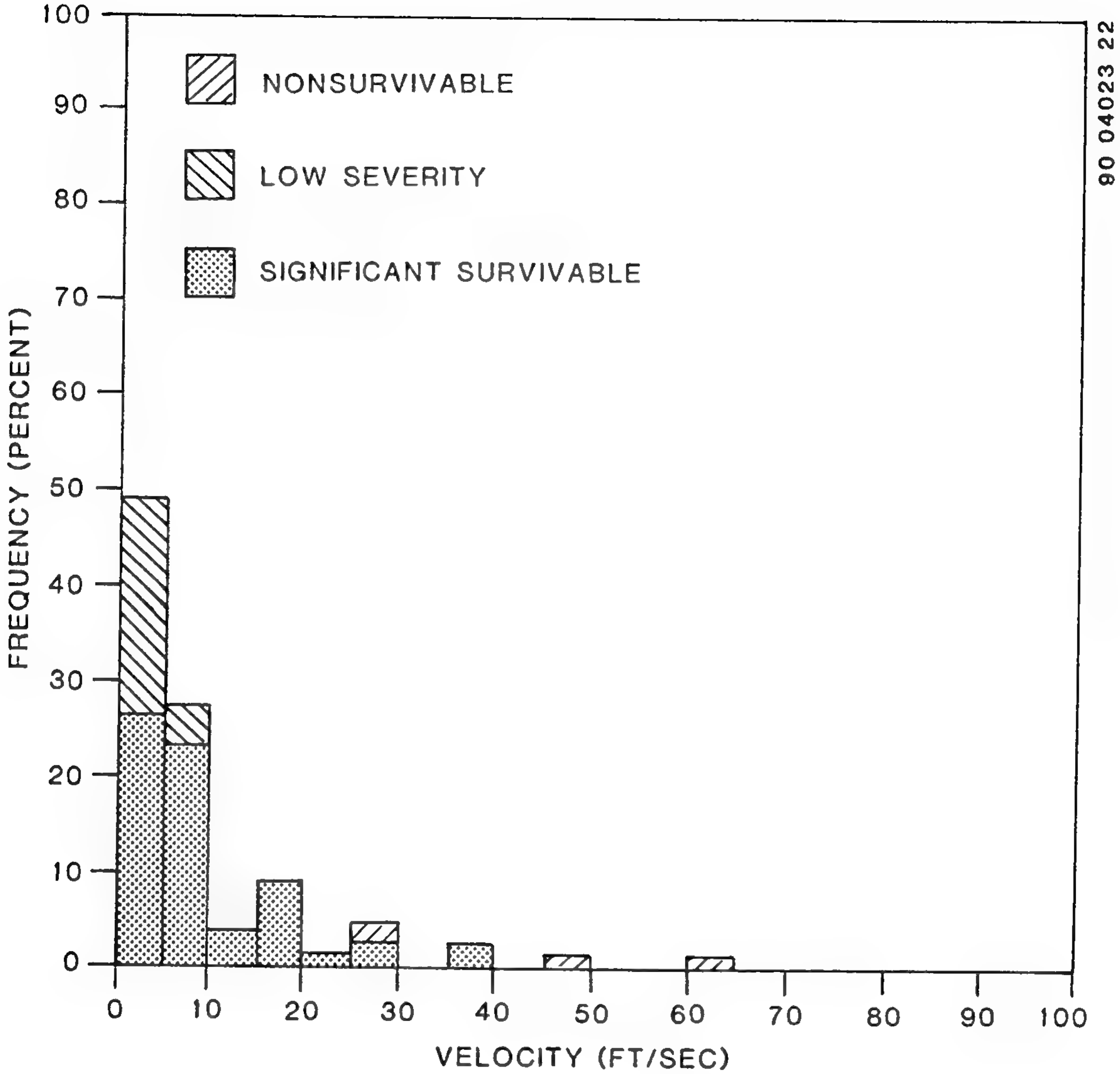


Figure 37.
Frequency of occurrence of vertical impact velocity, weight class B (87 accidents).

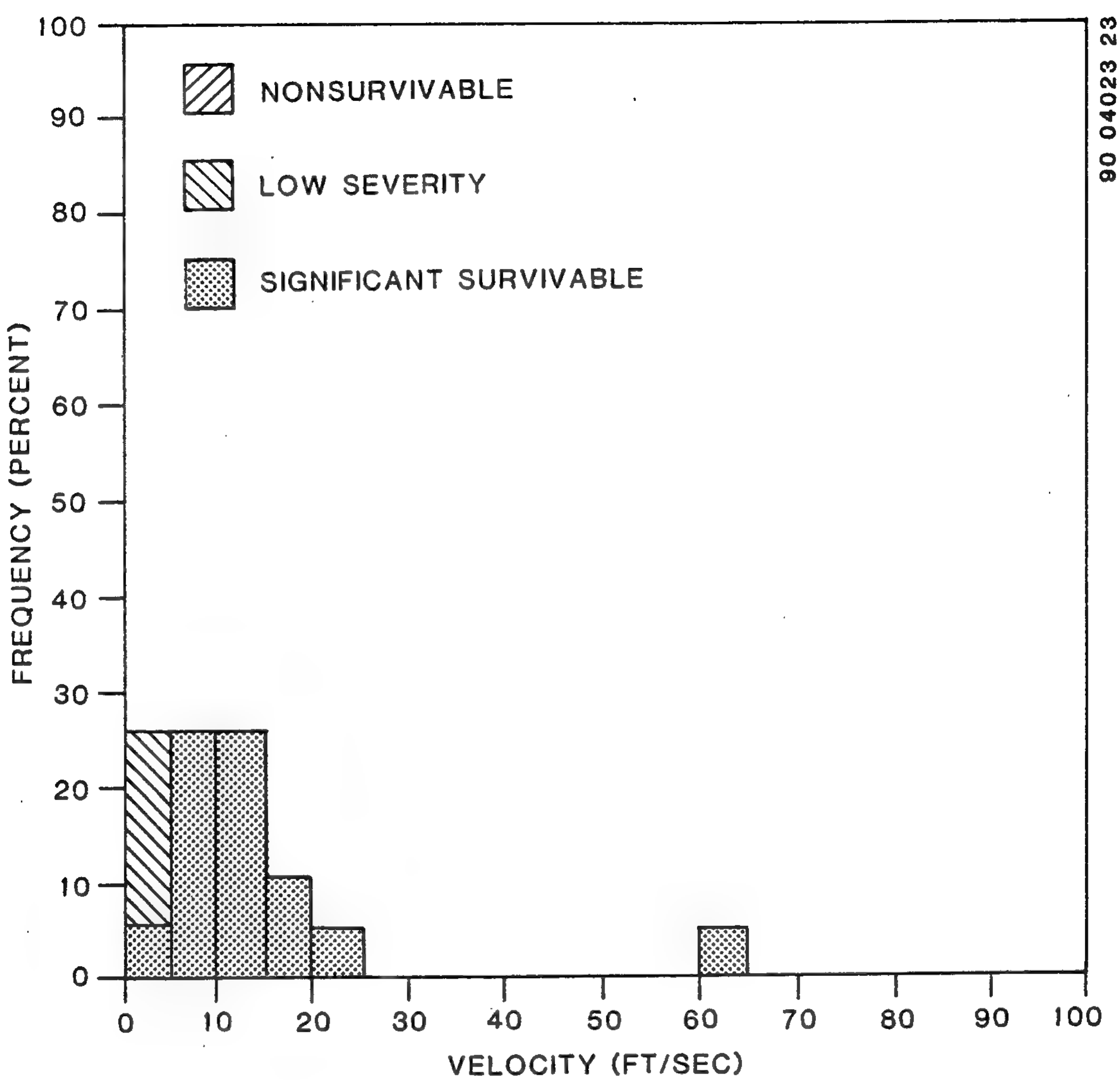


Figure 38.
Frequency of occurrence of vertical impact velocity, weight classes C and D (19 accidents).

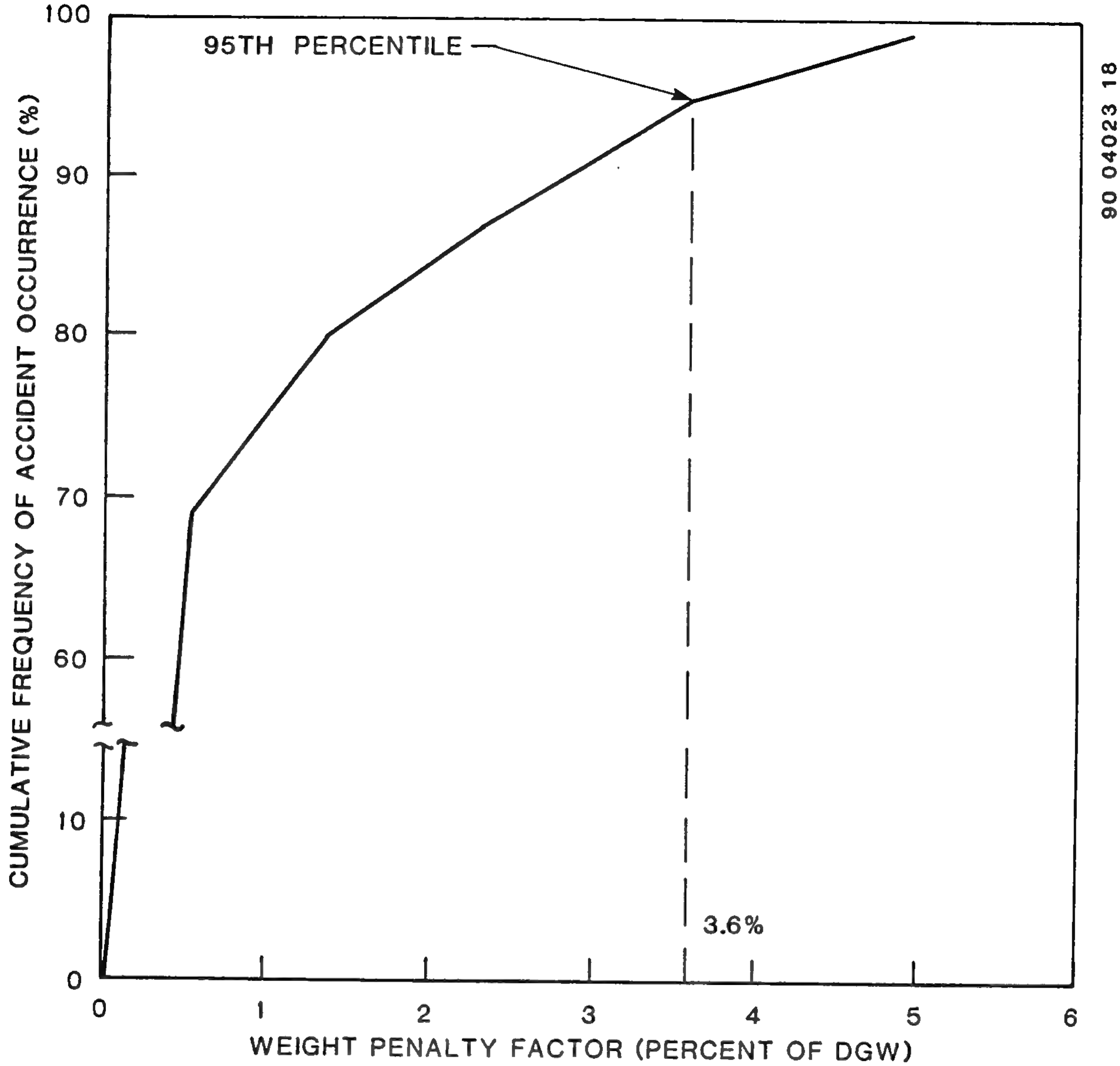


Figure 39.
Correlation of cumulative accident frequency and weight penalty factor for weight class A.

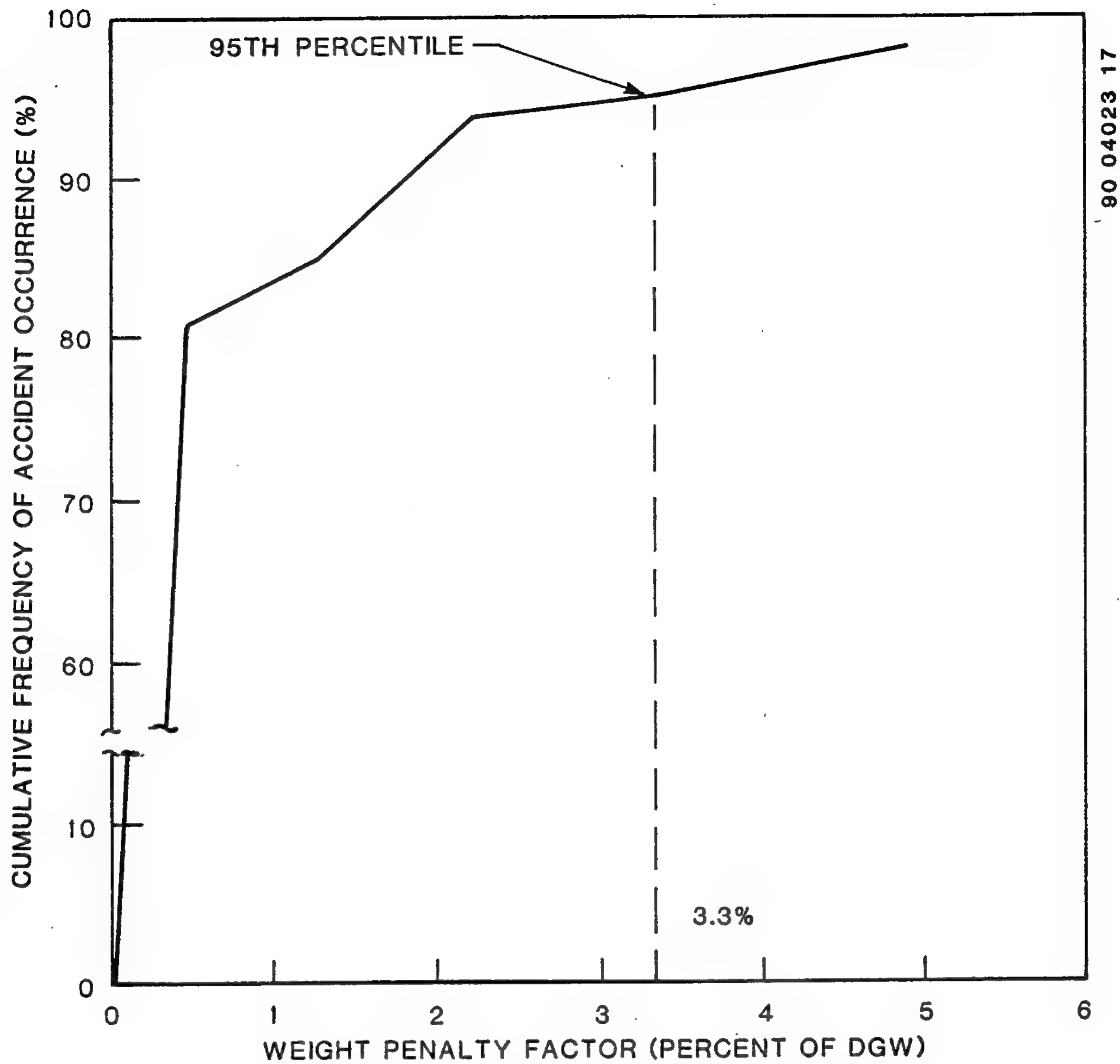


Figure 40.
Correlation of cumulative accident frequency and weight penalty factor for weight class B.

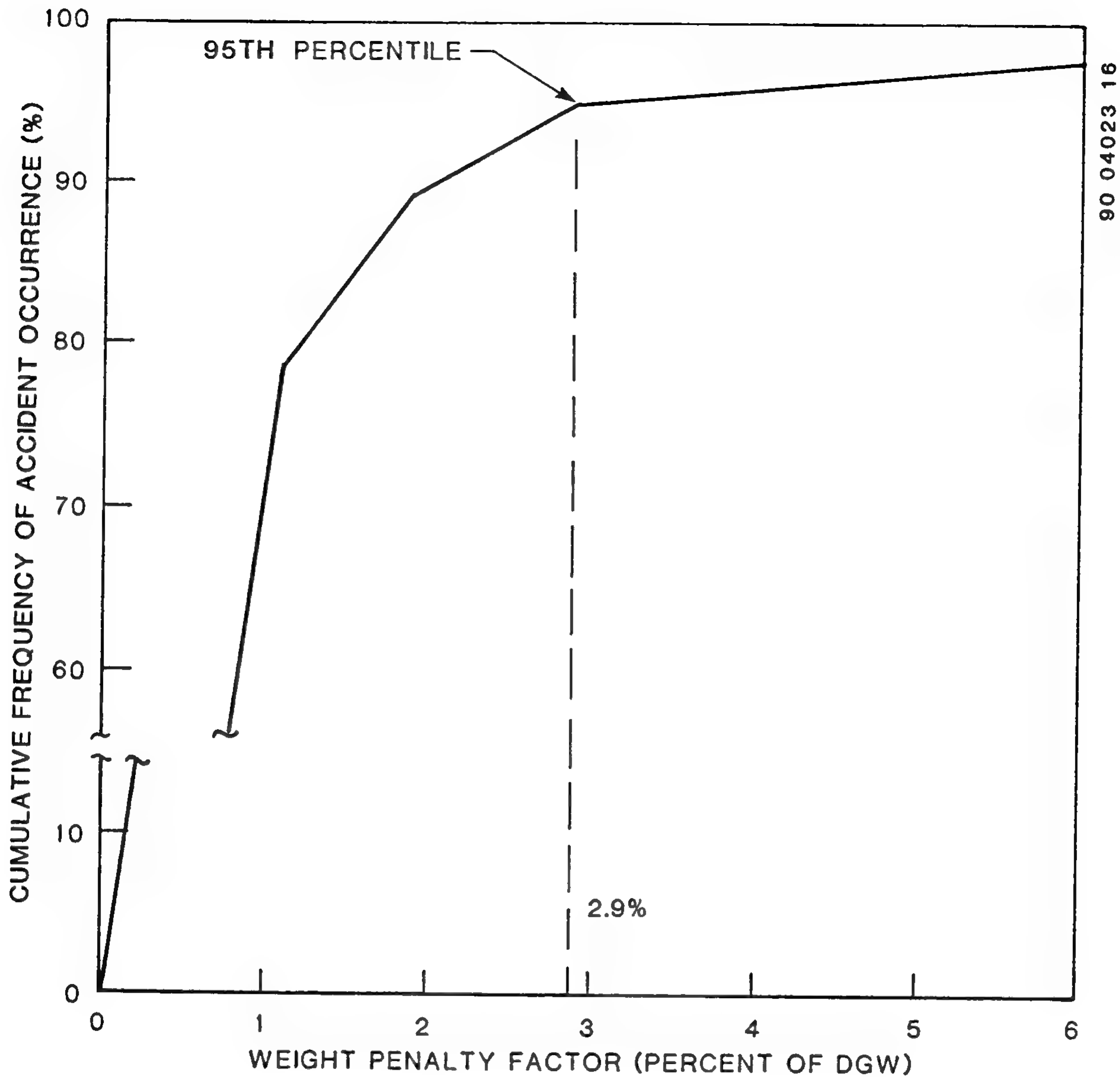


Figure 41.
Correlation of cumulative accident frequency and weight penalty factor for weight class C.

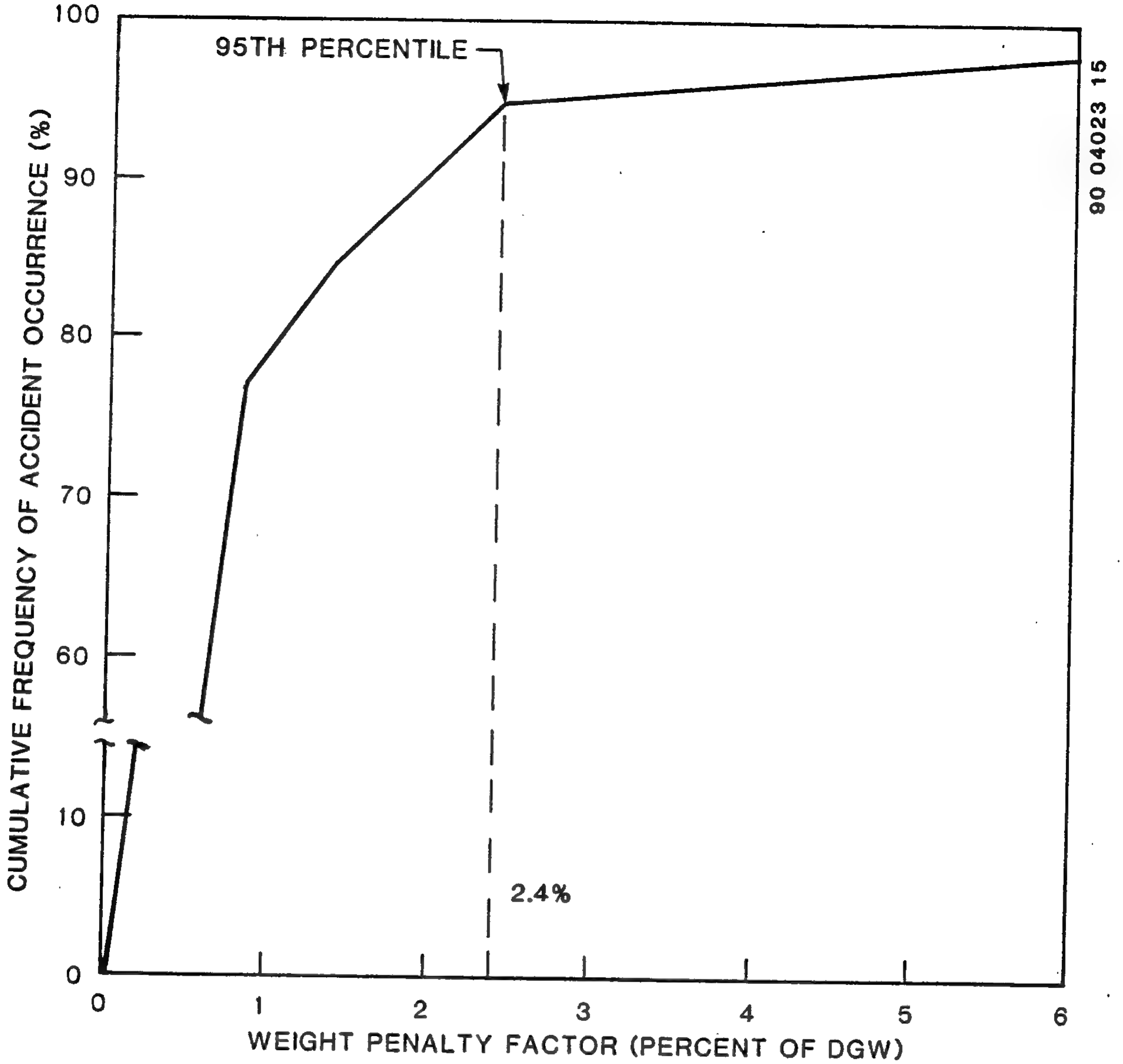


Figure 42.
Correlation of cumulative accident frequency and weight penalty factor for weight class D.

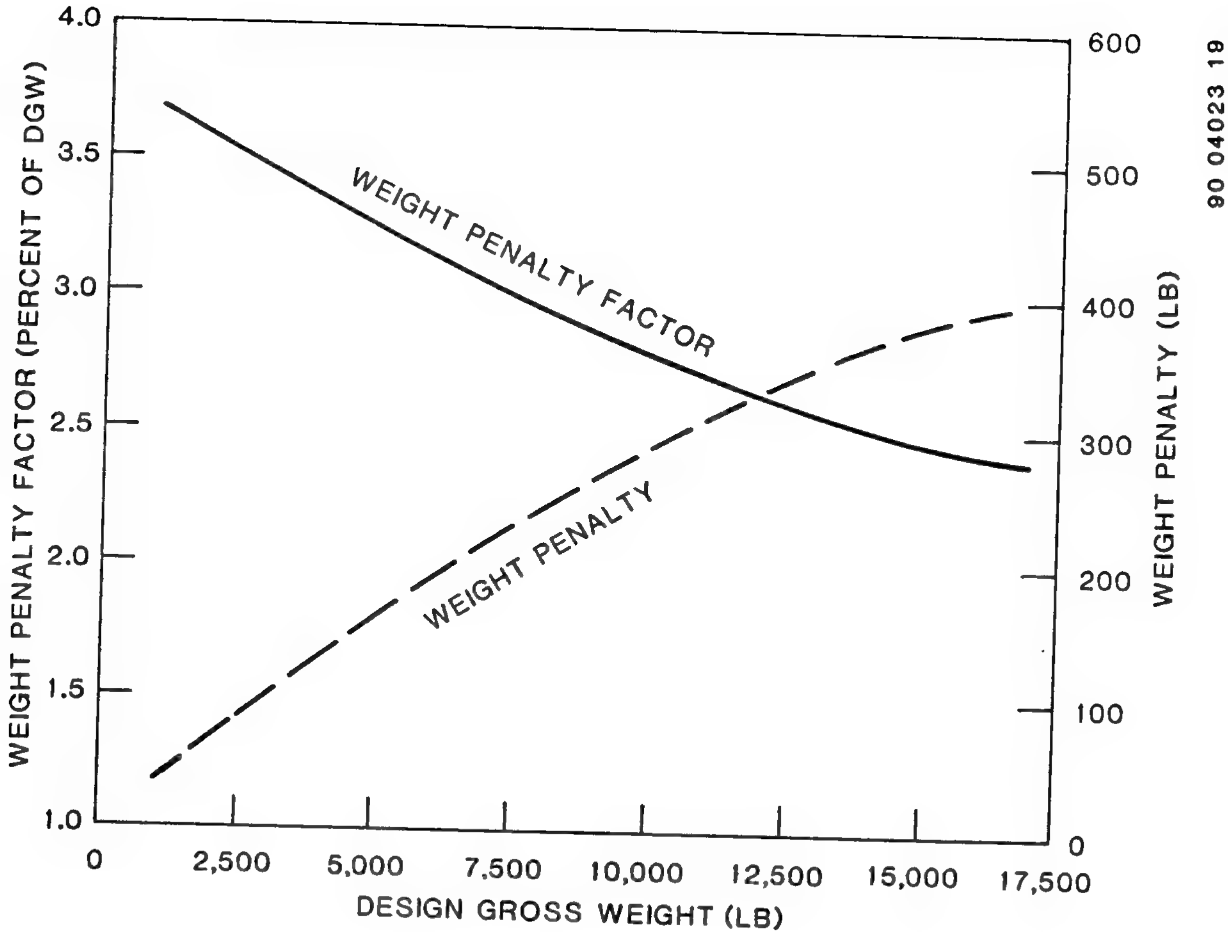


Figure 43.
Trends in weight penalty factor and weight penalty as a function of design gross weight for the 95th-percentile survivable vertical impact velocity.

6.0 CRASH IMPACT DESIGN AND TEST CRITERIA

The data presented in this study indicate that improved crash resistance for civil rotorcraft is both feasible and potentially effective in minimizing injuries and fatalities. Crash resistance technology does exist to achieve levels of crash protection significantly higher than the civil crash environment would warrant; however, accident data does not support this approach. Rather, this report identifies appropriate levels of crash resistance for civil rotorcraft. These levels of crash resistance would provide a significant injury reduction potential for civil rotorcraft and would not impose unwarranted weight penalties on future rotorcraft designs.

The remainder of this section focuses on the development of design and test criteria that is realistic for the civil rotorcraft crash environment. Similar criteria were presented in Reference 1; however, these criteria were based solely on impact velocity requirements. Since the time that the Reference 1 criteria were formulated, a number of developments have arisen which would alter them. Specifically, the analyses presented in this report validate the selection of specific impact levels from an injury reduction standpoint. Also, dynamic testing standards have been established for seats in newly certificated rotorcraft (Reference 72). And Reference 1, among other studies, has caused the rotorcraft manufacturers to assert a position on improved crash resistance now that published data indicate the potential benefits (References 68 and 69).

The identified approach to developing design and test criteria is based on providing protection up to and including the 95th-percentile survivable impact velocities defined in Section 5.1 As discussed, this level of protection would provide a significant potential to reduce injuries and fatalities. Also, the 95th-percentile survivable level of protection appears to be both reasonable and attainable within the development period of the next generation of commercial helicopters. The identified impact velocities for design of new rotorcraft models are shown in Table 20. These velocities were used as the basis for formulating other design and test criteria.

Table 19.
Impact velocities for design
of new rotorcraft models

Direction Along Aircraft Axis	Design Velocity Change (ft/sec)
Vertical (downward)	26
Lateral	10
Longitudinal (forward)	50

6.1 ROTORCRAFT IMPACT CRITERIA

Evaluation of crash scenarios described in Reference 1 indicates the need for a series of design criteria for the overall aircraft. These criteria represent a significant percentage of the expected crash conditions for the civil rotorcraft fleet. Figure 44 identifies the three impact conditions: high-speed, longitudinal impact; pure vertical impact; and rollover. Over 50 percent of the accidents evaluated in Reference 1 would fall into one of these three categories. Because a large number of accidents were not found in any of the remaining types of impact conditions defined in Reference 1, it is believed that these impact conditions do not warrant a specific crash resistance design criteria. However, it should be noted that the occurrence of wirestrike (one specific type of accident) could be greatly reduced by the incorporation of an effective wirestrike protection system.

The three design conditions shown in Figure 44 would ensure a protective shell for the occupants under a range of impact conditions. Further, an airframe designed to meet impact Condition No. 1 would need to incorporate underfloor structure that minimizes plowing, thus reducing structural deformation and lowering inertial loads. The vertical impact condition, Condition No. 2, ensures that the individual elements of the energy management system can function as an overall, effective system to decelerate the aircraft and provide a tolerable acceleration environment for the occupants.

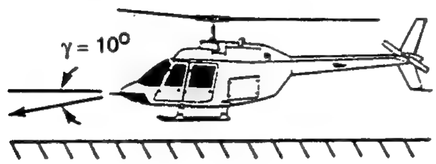
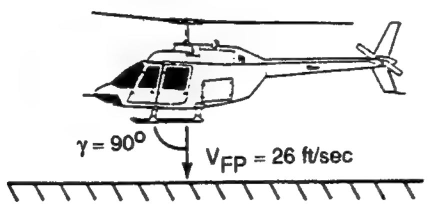
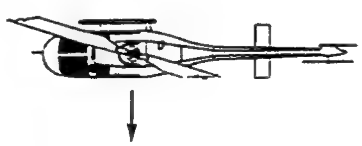
Data suggest that the three impact conditions shown in Figure 44 be considered as design criteria. These conditions need to be considered early in the airframe design process, when an analytical approach would most likely be used to support an airframe design capable of meeting these conditions. For the certification process it would be desirable to demonstrate compliance with Condition No. 2 in Figure 44 by airframe testing, or an alternative analytical method supported by component testing.

6.2 COMPONENT DESIGN AND TEST CRITERIA

Four major components play a critical role in achieving crash resistance in rotorcraft. These four components include the landing gear, seating systems, fuel systems, and components for retaining high-mass items. The performance of each of these systems must be consistent with the expected crash environment to achieve a balanced crash-resistant design. Each of these systems must function as part of the overall aircraft design to comply with all aspects of the impact scenarios shown in Figure 44. Whereas it is difficult and costly to test the entire aircraft to the defined impact scenarios, the individual components can often be designed and tested independently to verify performance. This section discusses design and test criteria for each of the four systems to be consistent with the overall identified criteria for the aircraft.

6.2.1 Landing Gear Criteria

Landing gear play an important role in the overall energy absorption system of a rotorcraft. In crashes of a rotorcraft with relatively flat impact conditions, the gear deform while slowing the aircraft vertical velocity. It was determined in the Reference 1 study that the gear may have functioned in approximately 53 percent of the rotorcraft accidents reviewed. In the remaining 47 percent of the accidents, either the terrain type (such as water), terrain features, or impact attitude rendered the gear ineffective. Considering the relatively low percentage of accidents in which the gear actually functioned, a significant amount of the vertical energy absorption capability should be placed in other system components such as the underfloor structure and seating systems.

Condition Number	Impact Condition*	Impact Surface	Intent
1		Soft Ground	High-speed, run on landing. Major impact deforms/removes gear, damages fuselage understructure. "Plowing" of fuselage should be prevented.
2		Hard, smooth surface	Pure vertical impact. All energy absorption capability of gear depleted. To minimize hazard to occupants, fuselage under-structure and/or seats must attenuate deceleration pulse. Overhead structure and high mass items must stay in place.
3		Soil or rigid surface	Impact in 90-degree roll attitude to either side. Contact forces distributed over airframe surface. Internal volume should not be reduced by more than 15 percent.

*γ = Flight path angle.
V_{FP} = Flight Path Velocity.

Figure 44.
Defined rotorcraft impact conditions.

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However, increased gear energy absorption capability would prevent fuselage/ground contact in a large number of less severe accidents. The savings in structural impact damage may make increased gear capabilities advantageous in some specialized rotorcraft designs.

An analysis of rotorcraft conforming to FAR Part 27 indicates that the 10.23 ft/sec reserve energy sink speed (V_{RE}) provides approximately 15.5 percent of the energy absorption capability required to dissipate the 95th-percentile vertical impact speed of 26 ft/sec. This is based on the ratios of kinetic energy at impact, i.e.,

$$\text{Percent of energy-absorbing capability} = \frac{\frac{1}{2} m V^2_{RE}}{\frac{1}{2} m V^2_{95}} = \frac{(10.23 \text{ ft/sec})^2}{(26.00 \text{ ft/sec})^2} = 15.5 \text{ percent}$$

A similar analysis of rotorcraft conforming to FAR Part 29 indicates that the landing gear, with a V_{RE} of 8.02 ft/sec, would be capable of absorbing 9.5 percent of the impact energy for a 26 ft/sec vertical impact.

The detailed analytical study of landing gear and fuselage described in Appendix A examined different mixes of energy absorption in the landing gear and fuselage. The landing gear contribution that was examined ranged from 15 to 50 percent. The analysis described in Appendix A resulted in the conclusion that an optimum mix of energy absorption was achieved with a ratio of approximately 20 percent in the landing gear and 80 percent in the fuselage/seat combination. The optimization criterion for the analysis was minimization of overall aircraft weight. The 20/80 percent ratio was not found to be sensitive to aircraft size. The 20 percent energy absorption contribution for the landing gear would indicate a reserve energy sink speed of 11.63 ft/sec.

The analysis indicates that an energy absorption ratio of 20/80 percent in the landing gear and fuselage, respectively, would minimize rotorcraft weight. However, to identify this ratio as a criterion would dictate a design approach rather than a performance specification. It would be inappropriate to specify the absorption ratio in the FAR's; however, the analysis does suggest several considerations for landing gear requirements. Nothing in the analysis would suggest a reduction in V_{RE} from the present values. On the contrary, data would suggest higher V_{RE} values. Also, in order for the landing gear to comply with the overall aircraft impact requirements, they must be capable of absorbing impact energies over a range of impact velocities (i.e., up to 26.0 ft/sec) and at off-axis impact conditions.

Landing gear design requirements should consider both symmetric, vertical impacts and off-axis impacts. The recommended design criteria should be a reserve energy sink speed, V_{RE}, on a hard, flat surface with the aircraft at maximum gross weight and 2/3-G rotor lift factor. Further, the statistical database for civil rotorcraft indicates the need for the gear to function over a range of pitch and roll attitudes. Figure 45 shows a landing gear design envelope for civil rotorcraft consistent with these data. Numerous studies (such as References 14, 36, and 38-41) have shown that it is unrealistic from a weight standpoint to require a landing gear design to function at constant performance over the pitch and roll envelope. This is reflected in the recommended design envelope shown in Figure 45.

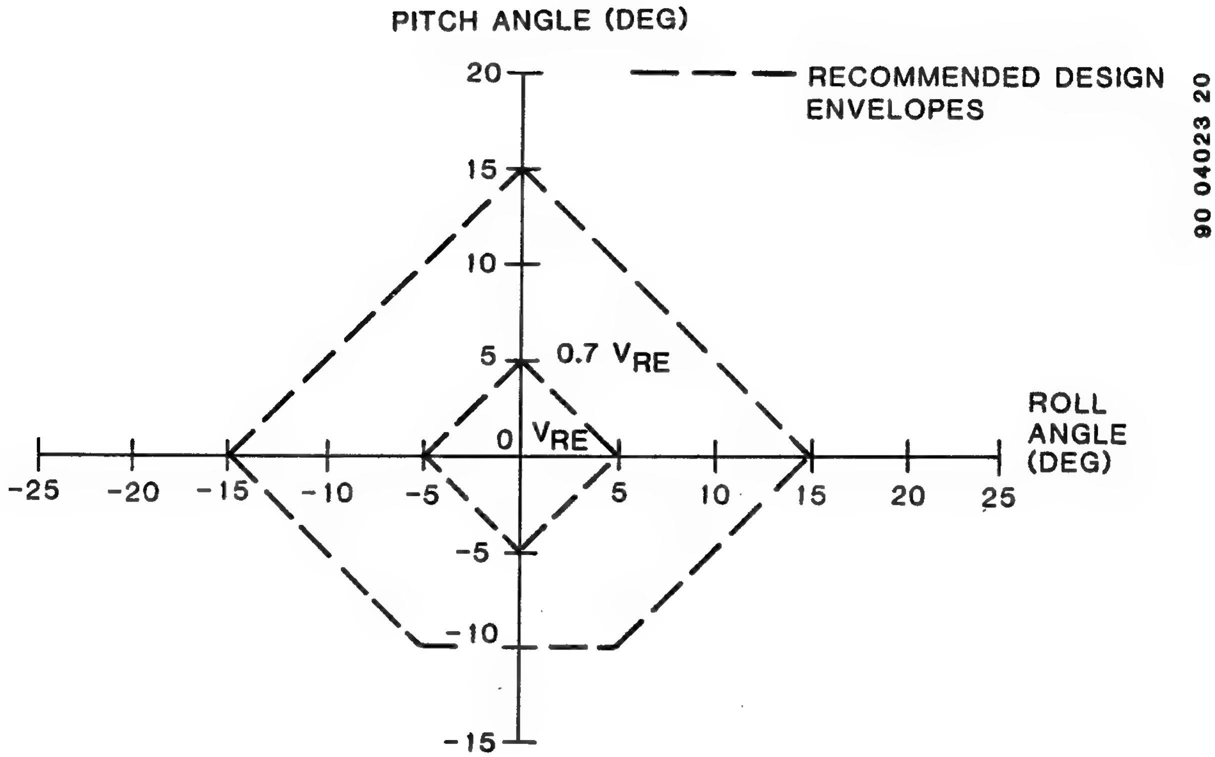


Figure 45.
Identified landing gear design envelope.

Several other criteria are suggested by the analyses. The first criterion is that the gear should be designed to function effectively over the expected range of impact velocities, i.e. 0 to 26 ft/sec vertical contact velocity. The purpose of this requirement is to ensure that rate sensitivity, which is found in a number of energy-absorbing devices such as oleo struts, does not hinder gear performance. Specifically, the landing gear should be capable of decelerating the aircraft under the following two conditions:

1. Deceleration of the aircraft from the reserve energy velocity, V_{RE}, to 0.

2. Deceleration of the aircraft from the recommended vertical impact velocity of 26 ft/sec until fuselage contact.

Under these specified conditions, the landing gear are absorbing the same amount of crash energy, although at different rates.

The second design consideration is the crash resistance performance of retractable landing gear. The two design conditions listed above should be applied to retractable landing gear in the unretracted position. It is very difficult to achieve substantial amounts of energy absorption in retracted gear. Therefore, the analysis would indicate that vertical impact criteria for rotorcraft with landing gear in the retracted state should be reduced appropriately to account for the energy not absorbed by the landing gear. To comply with this condition, the subfloor should be capable of decelerating the aircraft from the following velocity:

$$V_{FUSELAGE} = \sqrt{(26.0\ \text{ft/sec})^2 - V_{RE}^2}$$

Previous developmental programs have shown that it is highly desirable to verify the effectiveness of the landing gear energy absorption capability. Ideally, a drop test would be conducted at the 0-degree pitch, 5-degree roll attitude at the gross weight of the aircraft using a jig drop test for wheeled gear and a frame drop test for skid gear. Further, it is recommended that the vertical impact velocity should be a minimum of 26 ft/sec. The performance of the gear at other pitch and roll attitudes, and impact velocities, could be verified analytically by a method such as that described in Reference 14, or by additional testing.

6.2.2 Seating Systems

Reference 1 contains an extensive discussion of design and test criteria for civil rotorcraft seating systems. The recommendations in Reference 1 formed the basis for subsequent actions by the FAA and the RARC of the AIA. The eventual outcome of these actions was a series of amendments to FAR Parts 27 and 29 requiring dynamic testing of seats and restraint systems and the adoption of human injury criteria as the measure of performance (Reference 72). Although the Reference 1 report was used as the basis for these amendments, the actual test criteria differed slightly from that recommended in Reference 1. A summary of the adopted seat standards to be imposed on newly certificated rotorcraft models is supplied below.

Each seat type or other seating device to be used by crew or passengers during take-off and landing must demonstrate compliance with two dynamic design conditions. Compliance must be demonstrated by dynamic testing, or an approved alternate method using some form of analysis. The two dynamic design conditions represent a predominately vertical impact and a longitudinal impact with yaw angle. The vertical impact condition emphasizes occupant vertical

loading in the seat and determines the effectiveness of design features provided to restrain and support the occupant, and to attenuate loads imposed on the occupant. Attenuating the loads reduces the risk of spinal compressive injury for an impact of this type. The longitudinal condition with yaw simulates a horizontal impact with a ground level obstruction. This condition evaluates the occupant restraint system, the potential for secondary head and torso impact with the structure, and the structural integrity of the seat. Figure 46 shows the two dynamic conditions for seat design and testing that were selected by the FAA.

The seat dynamic testing is to be conducted with a 170-lb anthropomorphic test device (ATD) as defined by 49 CFR 572, subpart B. Also, where floor rails, or floor or sidewall attachment devices are used to attach the seating devices to the airframe structure, the rails or devices must be misaligned in the tests with respect to each other by at least 10 degrees vertically (i.e., pitch out of parallel) and by at least a 10-degree lateral roll, with the directions optional, to account for possible structural warpage.

Compliance of a seat design with the two dynamic test conditions would be demonstrated by:

1. The seating device and attachment between the seating device and airframe structure remaining intact through the test.

2. The shoulder strap and lap belt remaining on the shoulder and pelvis of the ATD, respectively, during the test.

3. The head of the ATD not contacting any portion of the compartment, or if contact occurs, producing a head injury criteria (HIC) value of 1,000 or less.

4. Loads in an individual upper torso strap not exceeding 1,750 lb, or the combined load measured in dual straps not exceeding 2,000 lb.

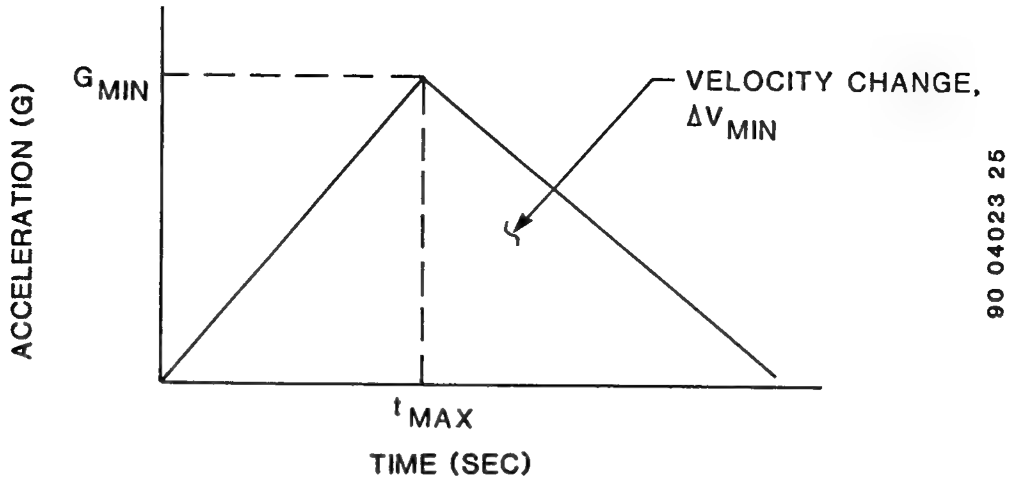
5. The maximum compressive load measured in the pelvis and lumbar spine of the ATD not exceeding 1,500 lb.

The dynamic conditions discussed above can be considered as both design and test criteria. The amendments to FAR Parts 27 and 29 also identify design requirements for static inertial load factors for occupant retention. These load factors to be used in seating system design are:

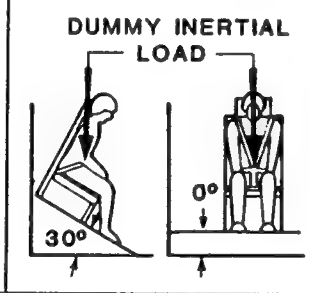
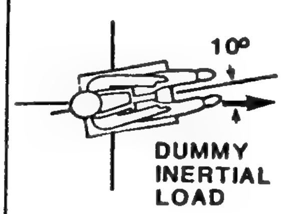
- Upward - 4 G
- Forward - 16 G
- Sideward - 8 G
- Downward - 20 G, after intended displacement of the seat device.

6.2.3 Equipment and High-Mass Item Retention Criteria

The amendments to FAR Parts 27 and 29 enacted in November 1989 (Reference 72) also specified increased ultimate inertial load factors for support structure of items which could injure an occupant if broken loose during an accident. The new load factors apply to each item of mass attached in an occupied area and high-mass items such as rotors, transmissions, and engines which could enter the occupied space. The ultimate inertial load factors for these items are shown in Table 21. The inertial load factors were based on the civil crash scenarios and are in agreement with the aircraft impact conditions described in Section 6.1.



a. Input acceleration pulse

Test	Configuration	Parameter	Limits
1		t_{max} G_{min} ΔV_{min}	0.031 sec 30 G 30 ft/sec
2		t_{max} G_{min} ΔV_{min}	0.071 sec 18.4 G 42 ft/sec

b. Two dynamic test conditions

Figure 46.
Seating system dynamic test conditions.

Table 20.
Inertial load factors for various equipment

Direction*	Ultimate Inertial Load Factors (G) Cabin Equipment	High Mass Item**
Upward	4	4
Forward	16	16
Sideward	8	8
Downward	20	20

NOTES
*In aircraft coordinate system.
**Includes, but not limited to, rotors, engines, and transmissions.

6.2.4 CRFS Criteria

Design and test criteria for CRFS's are difficult to directly correlate to the aircraft impact conditions identified in Section 6.1. The difficulty arises from the nature of fuel system design. The approach to fuel system design, particularly fuel cells, is primarily empirical. Therefore, it is difficult to develop a direct relationship between crash impact velocity and fuel system design. Fortunately, there has been extensive work to develop concepts for civil CRFS's by the RARC Crashworthiness Project Group to meet the impact conditions defined in Reference 1. The approach recommended by RARC was used in developing the CRFS's for the three generic rotorcraft described in Section 4.0. These recommendations were also considered by the FAA in formulating NPRM 90-24, (Reference 80).

Based on the recommendations of the RARC group and the practical lessons learned in developing the CRFS's for the three generic civil rotorcraft, design and test criteria could be identified. The general approach to designing civil CRFS's followed the guidelines set forth in MIL-T-27422B, Type II, Class A. These sections of the military specification govern the design of flexible fuel cell construction which is non-self-sealing (i.e., no ballistic protection). The overall goal of the specification is to achieve a CRFS design which:

- Minimizes potential ignition sources
- Contains the fuel in the fuel cells
- Prevents spillage from pulled and broken fuel lines

- Prevents spillage through the vent lines during a rollover or in any adverse postcrash attitude

- Uses a suction fuel feed system to prevent the continued pumping of fuel from a broken or separated fuel line.

Although the identified approach follows the guidelines in MIL-T-27422B, the specific component and material requirements have been modified to be consistent with the anticipated civil rotorcraft crash environment. The component and material requirements can be broken down into two categories: fuel cell construction and fuel line construction. The specific identified fuel system criteria to be used with the general approach outlined in MIL-T-27422B are listed in Table 22.

Table 21.
Identified criteria for civil rotorcraft crash-resistant fuel system (CRFS) design

Component	Criterion
Fuel cells	
Tear energy	Minimum of 20 ft-lb energy to sustain constant tear rate.
Impact penetration and tear	Drop 5-lb, pointed chisel from 8.0 ft. Tear shall not exceed 1.0 in.
Crash impact	The cell shall be filled to 80 percent of normal capacity with water and the air removed. Drop upon a platform from a height of 50 ft. No leakage after impact is allowable.
Fuel lines	
Line	Flexible lines with braided, metallic shielding used in all locations.
Leakage	Not more than 8.0 oz of fuel spillage per fitting will occur at failed junctures of lines and connections.
Structural attachment	Where attached to fuselage structure, a frangible attachment fitting should be used or sufficient extra line length be provided to accommodate structural deformation.
Fittings at major structural elements	Self-sealing breakaway couplings/valves should be used at all locations where the fuel line passes through fuselage structure.

7.0 SUMMARY OF RESULTS

The primary goal of this research program was to identify appropriate crash resistance technology for U.S. civil rotorcraft. Appropriate crash resistance technology was defined as technology consistent with the expected crash environment for civil rotorcraft and would not impose unwarranted weight and cost penalties. The approach taken to achieve this goal examined many aspects of civil rotorcraft crash protection. A survey was conducted to identify existing technology. The crash environment for civil rotorcraft was reexamined to determine a realistic crash protection level. Conceptual designs were prepared for three generic rotorcraft representing a significant portion of the civil fleet; and the weight penalty for adding crash protection to these aircraft was quantified. Finally, rotorcraft design and test criteria were prepared to be consistent with the identified protection level. Results from each of these tasks are summarized below.

The survey of crash resistance technology identified both strengths and weaknesses in the existing technology base. The survey examined analytical, design, and testing methodologies, as well as validation of these methodologies. A strong technological base was found to exist in aircraft, seat, and occupant analysis; knowledge of human tolerance to acceleration and impact injuries; energy-absorbing seat design; and materials and structures for energy-absorbing subfloors. This existing technology, much of it applicable to civil rotorcraft, was developed primarily under U.S. Government funding. There was a lack of information in the following areas of the technological base: energy-absorbing landing gear for 10 to 15 ft/sec impact levels; validation of lightweight CRFS concepts; effect of water impact on crash survivability; innovative, low-cost approaches for structural energy absorption; and, in general, crash resistance technology applicable to small rotorcraft of gross weight less than 2,500 lb. In the course of conducting the technology survey, it was noted that it would be helpful to consolidate the technical data on civil rotorcraft crash resistance into a design guide for use by manufacturers and component suppliers.

A previous study sponsored by the FAA (Reference 1) examined in detail the crash environment of civil rotorcraft. The data developed in that program were reexamined to define realistic levels of crash protection that could be justified by the potential reduction in injuries and fatalities. There were a number of interesting findings from the review of the crash environment data. Specifically, three significant findings from the earlier study need to be reaffirmed:

- The impact conditions for civil rotorcraft are substantially lower than for U.S. military rotorcraft
- A large percentage of civil rotorcraft accidents are potentially survivable
- The predominate hazards to occupant survival were, in order of importance: post-crash fires, seat failures, restraint system failures, and drowning.

The potential for occupant survivability in the current civil helicopter fleet was examined. A survivable accident was defined as that in which the acceleration levels were within limits of human tolerance and a sufficient occupiable volume remained for properly restrained occupants. It was found that vertical impact velocity had the most significant effect on survivability. For the current civil fleet, a vertical impact velocity of approximately 30 ft/sec was the

approximate transition point from survivable to nonsurvivable. Longitudinal and lateral impact velocities had a much less significant effect on survivability. However, a review of injuries and fatalities in these potentially survivable crashes portrayed a different picture. Approximately 11 percent of the occupants in these survivable accidents received serious injury and 6 percent received fatal injuries. An analysis was conducted to determine the impact levels at which the serious injuries and fatalities occur, and it was found that a disproportionate number of these severe injuries occurred in a narrow range of impact velocities just below the survivability limits for the aircraft. Even though only 10 percent of the occupants were involved in crashes in this range, their injuries resulted in 32 percent of the injury costs*. It was clear from this analysis that significant reductions in occupant injuries could be achieved if rotorcraft were designed to the following impact velocity levels:

- Vertical (downward): 26 ft/sec
- Longitudinal (forward): 50 ft/sec
- Lateral: 10 ft/sec.

Extensive work was conducted in the remaining tasks to definitize these crash protection levels and examine their effect on future rotorcraft designs.

Three generic rotorcraft designs were prepared to assess the effect of incorporating increased levels of crash protection. The three models represented weight classes B, C, and D in the four-class designation established in Reference 1. Table 23 shows the weight class designation and the characteristics of the generic rotorcraft models. Weight class A was not represented due to budgetary limitations and due to the relative lack of crash resistance technology for small rotorcraft in this weight class. Even though a design was not prepared for weight class A, it was believed that the trends established for the other weight classes could be extrapolated to represent this class. The conceptual rotorcraft designs included drawings of the overall configuration and structural, seat, and fuel system designs. The goal in preparing the designs was to provide a basis for examining actual component designs that would provide varying levels of crash protection.

Table 22.
Weight class designations and characteristics of generic rotorcraft

Weight Class	Gross Weight Range (lb)	Percentage* of U.S. Rotorcraft Fleet	Generic Rotorcraft Characteristics: Gross Weight (lb)	Generic Rotorcraft Characteristics: Number of Crew and Passengers
A	0 - 2,500	29.6	-	-
B	2,501 - 6,000	55.4	4,100	5
C	6,001 - 12,500	11.5	8,740	12
D	>12,500	3.5	16,200	19

*Based on rotorcraft registered in October 1988.

*Injury costs were based on FAA projected values.

A trade-off analysis was conducted to examine the weight penalty associated with varying levels of crash protection. The baseline for this analysis was the three generic rotorcraft models with equipment designs which would meet the current FAR requirements. Four higher levels of crash protection were examined for each of the three generic rotorcraft. The primary variable in this analysis was the vertical impact velocity; the four higher levels of crash protection which were examined were: 14 ft/sec, 20 ft/sec, 26 ft/sec, and 32 ft/sec. The weight penalty for each crash-resistant component or system was established at the baseline and the four higher levels of crash protection. The result of the trade-off analysis was a relationship between crash protection level and weight penalty for each of the generic rotorcraft. At the 26 ft/sec vertical impact velocity level, which was identified as the optimum protective level for civil rotorcraft, weight classes A, B, C, and D would experience weight penalties of approximately 3.6, 3.3, 2.9, and 2.4 percent design gross weight, respectively. Although it is believed that weight penalties of this magnitude can be accommodated, it is apparent that the smaller weight classes carry a higher penalty to achieve the same level of crash protection.

The work that was conducted to identify the appropriate crash protection levels, and the understanding that was gained through development of crash-resistant systems for the three generic rotorcraft, led to the formulation of design and test criteria. The criteria that were developed covered overall aircraft impact criteria, as well as component criteria. Design and test criteria were established for landing gear, fuselage subfloor structures, seating systems, high-mass item retention, and fuel systems. The criteria that were established for seating systems and high-mass item retention were found to be consistent with criteria defined in the recently enacted rule changes to FAR Parts 27 and 29.

8.0 CONCLUSIONS

1. A detailed analysis of the civil rotorcraft crash environment was conducted to determine appropriate levels of crash protection for future rotorcraft.

2. The level of crash protection identified in this report as appropriate for civil rotorcraft is significantly below that specified for U.S. military rotorcraft in MIL-STD-1290(AV). The differences in crash protection levels for the two groups of rotorcraft is primarily due to significant differences in the identified crash environments.

3. A survey was conducted of crash resistance technology to determine the applicability of such technology to civil rotorcraft. In some areas the technology is well established due to extensive research sponsored by the U.S. military and the FAA. However, in several other key areas there is a lack of proven technology for civil rotorcraft. This is especially true of crash protection technology appropriate for very small rotorcraft (less than 2,500 lb design gross weight).

4. An effective method was developed to examine the effect of incorporating crash resistance technology in civil rotorcraft. Three generic rotorcraft designs, of varying sizes, were developed to determine the effect of incorporating various levels of crash resistance. In all three cases, it appeared feasible to achieve the defined levels of crash protection for civil rotorcraft.

5. The effect of incorporating crash protection in civil rotorcraft was examined by determining the consequent weight penalty. The benefits of incorporating crash protection features were also examined through an evaluation of the potential for injury reduction. It is apparent that significant benefits would be achieved by incorporation of crash-resistant features in civil rotorcraft.

6. Crash-resistant criteria were formulated for civil rotorcraft. It was found that these criteria were consistent with, and would enhance the benefits of, dynamic performance standards for seats and restraints set forth by the FAA.

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APPENDIX A

SUMMARY REPORT ON AIRFRAME CRASH RESISTANCE WEIGHT PENALTY ASSESSMENT

1.0 INTRODUCTION

The primary factor inhibiting the incorporation of crash resistance in rotorcraft is the associated weight and cost penalties. This appendix discusses an approach for estimating weight penalties of various subsystems based on the level of inherent crash resistance. The data presented are based on empirical correlations to actual designs performed by Bell Helicopter Textron Inc. (BHTI). The landing gear and fuselage weight trends were developed by BHTI under a separate contract. The parametric analyses considered weight penalties for various aircraft subsystems. Figure A-1 shows schematically the steps required in BHTI's analysis to account for the components in the landing gear and fuselage affected by crash resistance design. The landing gear analysis and fuselage analysis were performed separately. The two analyses were then combined to provide an overall trade-off analysis for the entire airframe. The following sections describe the methodology used by BHTI to calculate weight penalties and conduct the trade-off analysis.

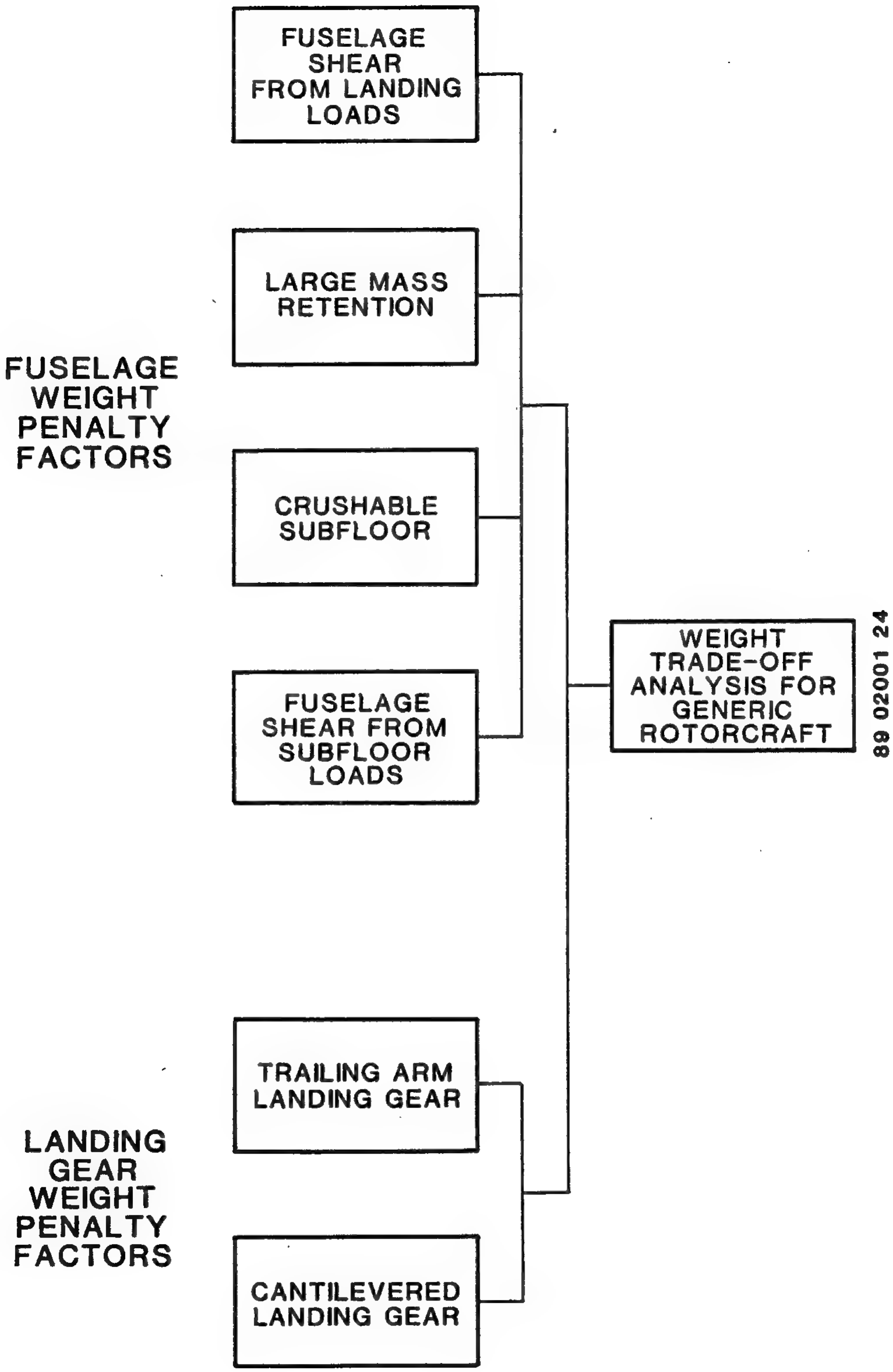


Figure A-1.
Weight penalty factors for weight trade-off analysis.

2.0 INFLUENCE OF ROTORCRAFT DESIGN PARAMETERS

For this study the inputs to the parametric equations were based on the three generic aircraft configurations described in Section 4.0 of this report. The following design parameters were required to determine the weight penalty associated with providing varying levels of crash resistance protection:

- Design gross weight
- Geometry and configuration of fuselage
- Fuselage construction
- Material type
- Flight load factors
- Crash load factors.

The importance of these parameters in determining the crash resistance weight penalty is discussed below.

2.1 DESIGN GROSS WEIGHT AND BASIC BODY WEIGHT

The design gross weight (DGW) was selected as the baseline parameter for calculation of the crash resistance weight penalty. However, the BHTI parametric equations for fuselage weight penalties were based on basic body weight (BBW). The BBW presents the primary flight load structure required for a given configuration based on shear forces and moments generated for standard G loading. The validation of BHTI's correlation for BBW based on 20 civil and military rotorcraft designs is shown in Figure A-2. Using the parametric equation established by BHTI, the BBW was calculated for each of the three generic rotorcraft. Table A-1 shows the comparison of BBW and DGW for the three rotorcraft. For the three

Table A-1.
Primary Fuselage Basic Body Weight
Versus Design Gross Weight

Generic Configuration	Design Gross Weight (lb)	Basic Body Weight (lb)	Percent of DGW (%)
Light	4,100	259	6.3
Medium	8,740	578	6.6
Heavy	16,200	1,080	6.7

generic rotorcraft, the BBW parameter ranged from 6.3 to 6.7 percent of the overall DGW. It is important to note that the weight of the airframe structure represents a surprisingly small percentage of the rotorcraft gross weight.

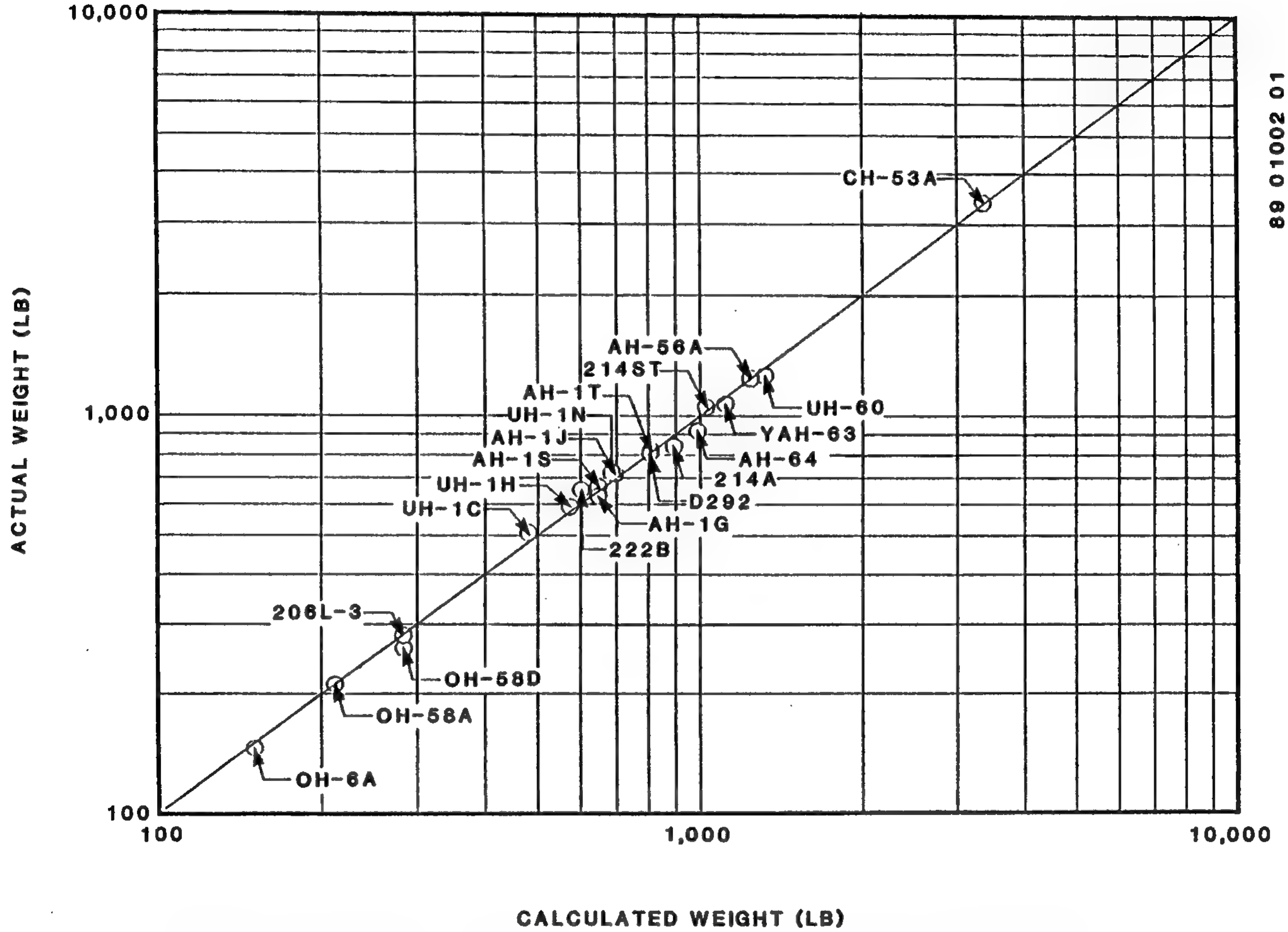


Figure A-2.
Basic body weight correlation used to validate parametric equation.

2.2 GEOMETRY AND CONFIGURATION

The parameters used in the study to describe fuselage geometry and overall configuration are shown in Figure A-3. Some of the other necessary parameters included the number of engines, the maximum speed obtainable, fuselage size, amount of fuel, number of passengers, and the nature of the fuselage (i.e., cantilevered or framed sections) to determine the baseline structure. Additional design parameters for the three generic rotorcraft were discussed in Section 4.0 of this report. The configuration of the rotorcraft designs were critical for defining available space for incorporating crash resistance features and in defining the geometry which placed limitations on the amount of crash resistance that could be incorporated. Significant effort went into the generic designs to ensure that they were representative of their weight classes because of the effect of geometry and configuration on achieving crash resistance.

2.3 FUSELAGE CONSTRUCTION

The construction of the fuselage is an important parameter influencing the baseline weight of the aircraft. Minimization of fuselage weight is based on the efficiency of load paths through the frames, bulkheads, and subfloor, as well as the appropriate selection of materials to sustain large deformations and absorb crash energy. The analyses presented here are based on the assumption that energy absorption concepts can be incorporated into typical fuselage structure. Structural details were presented in Section 4.0 for each of the generic rotorcraft fuselage designs. Fuselage construction also played a major role in defining configuration of the fuel system and routing of fuel lines which influenced the crash resistant fuel system (CRFS) design.

2.4 MATERIAL

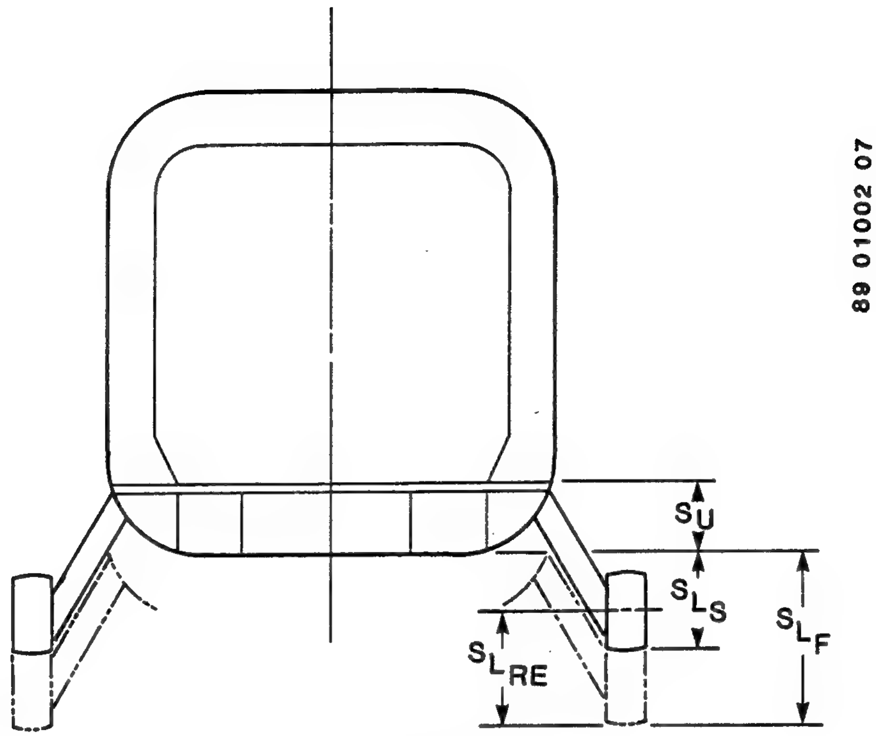
The type of material used in fuselage construction plays an important role in the way crash loads are distributed in the structure. Metal fuselages are considerably different than composite structures in weight, strength, stiffness, and particularly, their behavior under impact loading. Each type of material must be evaluated for its effect on the overall weight of the structure. All aspects of the material's influence on crash response of the design must be considered simultaneously. However, because of the difficulty in analyzing impact behavior, material parameters are primarily based on empirical test data. The empirical data come from both subcomponent testing and crash testing of entire fuselage sections.

2.5 FLIGHT LOAD FACTORS

The flight load factors determine the baseline for comparison of crash loads. The weight penalty analyses consider the flight load as a zero point since no penalty exists if the crash loads are less than or equal to the standard flight loads. The standard flight load factors chosen for this civil rotorcraft study were based on the factors for three of BHTI's civil helicopter models (206, 222, and 214ST) which are roughly comparable in size to the generic helicopters.

2.6 CRASH LOAD FACTORS

Fuselage crash load factors are based generally on the size of the crush zone, the material used, and the level of crash resistance protection required. Specifically, the depth of the crush zone will determine the distance over which the crash forces can be dissipated. This distance



CRITICAL DIMENSIONS

CONFIGURATION	S_U (IN.)	S_{L_F} (IN.)	S_{L_S} (IN.)	$S_{L_{RE}}$ (IN.)
LIGHT	5.5	18.5	14.5	18.5
MEDIUM	9.2	21.4	13.4	10.0
HEAVY	12.0	25.0	17.0	12.25

Figure A-3.
Generic helicopter geometry used in parametric equations for weight penalty factors.

in conjunction with the selected energy-absorbing material type will determine the force levels which will be transmitted into the fuselage structure. These transmitted forces influence design of other crash resistance components such as seats, fuel systems, and attachments for engines and transmissions.

3.0 CALCULATION OF FUSELAGE AND LANDING GEAR WEIGHT PENALTIES

The BHTI parametric correlations were used to determine weight penalties for each of the weight penalty factors described above. To assess the weight penalties with the parametric correlations, the ranges for geometric variables and other aircraft design variables had to be established. These variables determine the amount of energy absorption that can be accounted for by each part of the rotorcraft: landing gear, fuselage, and seats. Table A-2 shows the selected values of the variables that were used in the crash resistance analysis. A range was selected for each parametric variable to determine the sensitivity of the generic rotorcraft designs to varying levels of crash resistance. For example, the range of aircraft sink speeds was selected from 10.0 ft/sec to 32.0 ft/sec. The lower bound represents the reserve energy sink speed requirement defined in FAR Part 27. The upper bound represents the 95th-percentile civil rotorcraft accident level defined in Analysis of Rotorcraft Crash Dynamics for Development of Improved Crashworthiness Design Criteria*. The selected range of landing gear velocity change, ΔV_{LG}, was from 10.0 ft/sec to 15.25 ft/sec. Therefore, the landing gear would absorb 100 percent of the vertical crash energy at the lower bound of aircraft sink speeds and approximately 23 percent at the upper end of the aircraft velocity range. The average acceleration experienced by the aircraft during landing gear energy absorption, G_{LG}, was calculated from the available landing gear stroke, S_{LRE}, the landing gear velocity change (ΔV_{LG}), and the landing gear efficiency factor (η). The landing gear efficiency factor takes into account deviations from constant acceleration profile. The 85 percent value used for η in the analysis is representative of efficient, crash-resistant gear designs. The resulting range of the landing gear acceleration was 1.24 G to 5.1 G.

Fuselage energy absorption had a range of parameters similar to that used for landing gear. The available crush depth of the underfloor, Su, varied from 5.5 in. for the light generic rotorcraft to 12.0 in. for the heavy generic rotorcraft. Not all of the underfloor depth was considered to be available for crushing; therefore an efficiency factor, η, of 75 percent was used to represent deviations from a constant crush load and compaction of the crushed structure taking available space. The value of 75 percent was derived from actual subfloor crush tests. The amount of energy to be absorbed in the subfloor, as defined by the fuselage velocity change, ΔV_F, ranged from 0 (when the landing gear absorbed all of the impact energy) to 28.1 ft/sec. The fuselage velocity change was calculated from the difference between the aircraft crash energy and that absorbed in the landing gear. The remaining parameter, acceleration during fuselage crushing, G_F, was calculated based on the other defined parameters for the subfloor. G_F varied from 0 G when the landing gear alone were capable of decelerating the aircraft to 35.7 G at the highest impact velocity levels. The upper bound for G_F falls in the range achieved for energy-absorbing subfloors designed and tested by BHTI and NASA.

3.1 FUSELAGE WEIGHT PENALTY ASSESSMENT

The fuselage weight penalty was divided into the following four categories:

1. Weight penalty due to shear forces and moments generated by the landing gear crash loads.

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*Coltman, J. W., et al., Analysis of Rotorcraft Crash Dynamics for Development of Improved Crashworthiness Design Criteria, DOT/FAA/CT-85/11, U.S. Department of Transportation, Federal Aviation Administration, Technical Center, Atlantic City Airport, New Jersey, June 1985.

Table A-2.
Selected landing gear and fuselage energy absorption parameters for generic configuration crash resistance analysis

Generic Model	Aircraft Sink Speed (ft/sec)	Landing Gear Energy Absorption				Fuselage Energy Absorption			
		S_{LRE}	η	ΔV_{LG}	G^*_{LG}	S_u	η	ΔV_F	G^*_F
Light	10.0	18.5	.85	10.0	1.24	5.5	.75	0	0
Medium	10.0	10.0	.85	10.0	2.3	9.2	.75	0	0
Heavy	10.0	12.25	.85	10.0	1.9	12.0	.75	0	0
Light	14.0	18.5	.85	10.0	1.24	5.5	.75	9.6	4.2
Medium	14.0	10.0	.85	10.0	2.3	9.2	.75	9.6	2.5
Heavy	14.0	12.25	.85	10.0	1.9	12.0	.75	9.6	1.9
Light	20.0	18.5	.85	10.0	1.24	5.5	.75	17.2	13.4
Medium	20.0	10.0	.85	10.0	2.3	9.2	.75	17.2	8.0
Heavy	20.0	12.25	.85	10.0	1.9	12.0	.75	17.2	6.1
Light	26.0	18.5	.85	12.4	1.82	5.5	.75	22.9	23.7
Medium	26.0	10.0	.85	12.4	3.4	9.2	.75	22.9	14.2
Heavy	26.0	12.25	.85	12.4	2.8	12.0	.75	22.9	10.9
Light	32.0	18.5	.85	15.25	2.8	5.5	.75	28.1	35.7
Medium	32.0	10.0	.85	15.25	5.1	9.2	.75	28.1	21.3
Heavy	32.0	12.25	.85	15.25	4.2	12.0	.75	28.1	16.3

*The calculation for G factor is based on the following equation:

$$G = \frac{\Delta V^2}{2\, g\, S/12\, \eta}$$

2. Weight penalty due to large mass retention strength requirements for the engine and transmission.

3. Weight penalty due to the addition of subfloor crushing material.

4. Weight penalty due to shear forces and moments generated by the fuselage crush loads.

The weight penalty associated with each of these four factors is based on a percentage of the basic body structural weight and is a function of aircraft sink speed. Calculation of weight penalties for the three generic rotorcraft is presented in the following sections.

3.1.1 <u>Fuselage Weight Penalty Due to Landing Gear Crash Loads</u>

A portion of the fuselage weight penalty is incurred from structural additions required to handle bending moments or loads from the landing gear. Shear and moment diagrams were used to calculate a maximum crash bending moment. The shear levels were governed by the sink rate input into the parametric equations since the sink rate determines the landing gear load factors. The landing gear load factors included a 1-G baseline plus the crash load factor each gear would experience. A lift vector was also used in the analysis to account for the effect of the rotor on increasing landing gear load requirements. The resultant shear diagram was integrated over the length of the fuselage to determine the magnitude and location of a maximum moment. This moment was an approximation to the maximum crash moment exerted on the fuselage by the gear for a given sink speed. The resultant crash moment was divided by the maximum flight moment to yield the crash load factor for the system. This crash load factor was used to determine the weight penalty due to landing gear loads associated with each design. A correlation of the fuselage penalty to sink speed is shown in Figure A-4 for each of the three generic rotorcraft.

It is interesting to note that below approximately 13.5 ft/sec for the light and medium rotorcraft, and below 16 ft/sec for the heavy rotorcraft, the weight penalty has a negative value. This indicates that flight load factors are more significant in influencing the fuselage design loads. The negative values on the curves exist because these equations are based on comparing the maximum crash moment generated by a given landing gear configuration with standard flight moments. If the crash moment is less than the normal moment generated for flight loads, then the flight loads will govern the design. For the purposes of the trade-off analysis, a zero weight penalty was used when the flight loads governed the fuselage design.

It can also be seen in the correlations in Figure A-4 that fuselage weight is extremely sensitive to landing gear crash loads. In fact, if landing gear energy absorption capability were set at 20 ft/sec, a weight penalty of about 55 percent of BBW would be experienced in the light and medium generic rotorcraft. This would equate to actual weight penalties of approximately 142 lb and 318 lb for these two designs, respectively.

3.1.2 <u>Large Mass Retention Loads</u>

Retention of large mass items during crash loading is critical to providing sufficient crash resistance protection. Structural reinforcement is required when a given area of the aircraft is designed to withstand loads above normal flight and landing loads. In this case, the baseline used came from <u>FAR Part 29.561</u> on emergency landing conditions. This standard for existing aircraft defines a minimum strength for the support structure of 4 G for pylon and large mass

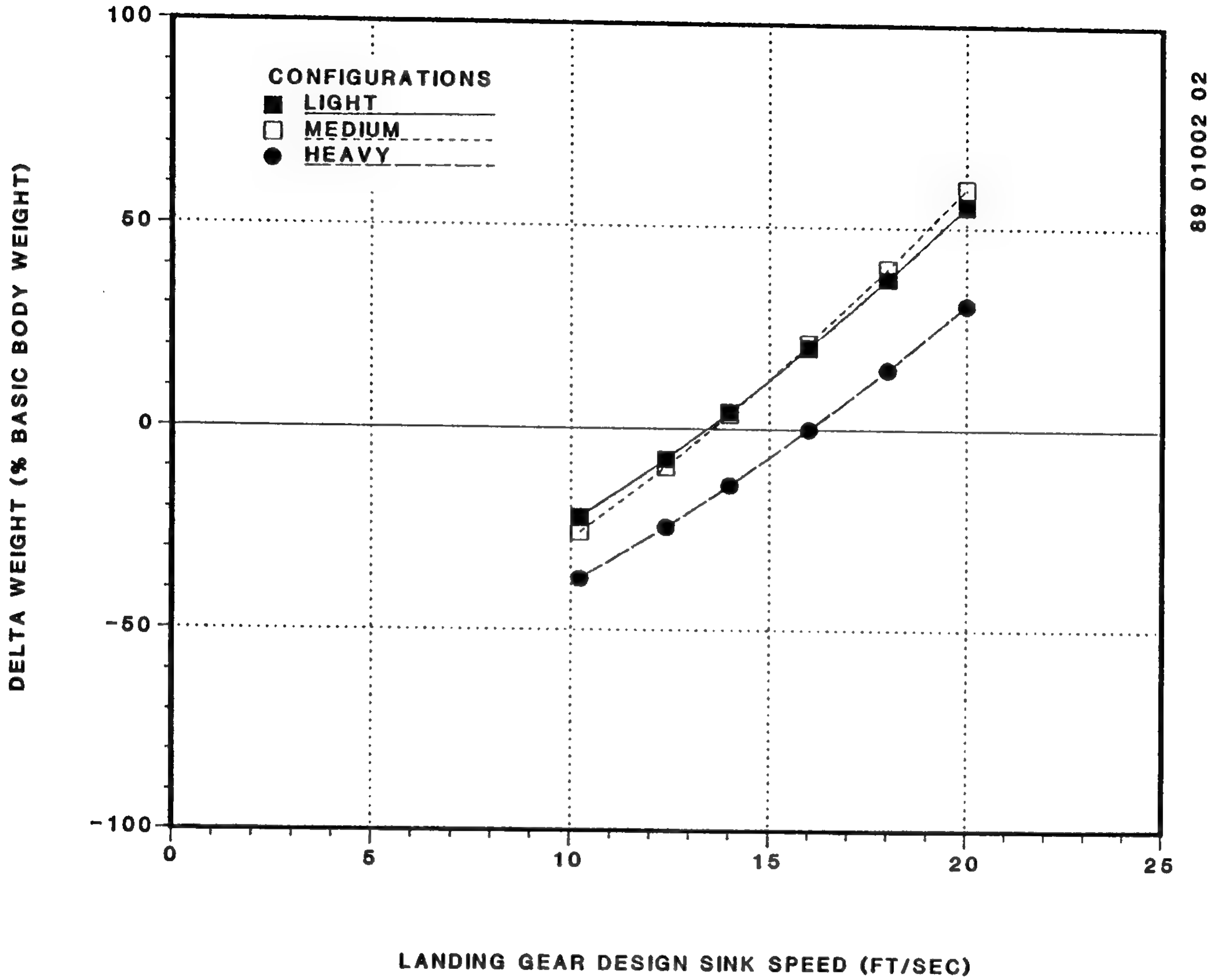

Figure A-4.
Fuselage weight increment from landing gear loads.

retention in the downward direction. The parametric equations used in this section were calibrated to achieve a zero weight penalty for the 4-G deceleration level. The ensuing analyses determined the weight penalty associated with any strength increase above this baseline value.

Figure A-5 contains two curves for each generic configuration representing the fuselage weight penalty associated with retention strengths for the engine and transmission. The sink speeds here define the amount of energy to be absorbed by the fuselage only.

The parametric correlation for large mass retention indicates that the weight penalty falls in the 0 to 10 percent range category for both the engine and transmission depending upon fuselage sink speed requirement. The analysis indicated that the weight penalties experienced for the light generic rotorcraft (as a percent of BBW) are far greater than for the other two size categories.

3.1.3 Energy-Absorbing Crush Material

Extra crush material in the subfloor structure is another source of add-on weight associated with making the fuselage crash resistant. Figure A-6 details the estimated amount of weight penalty associated with varying levels of crash protection. The estimate used to determine this curve is based on BHTI's ACAP subfloor configuration, which was designed to meet the Army's MIL-STD-1290 specifications for a 42 ft/sec crash. The ACAP aircraft design experienced a 3.6-percent weight increase in BBW due to its use of a Kevlar®/epoxy sandwich energy-absorbing concept in the subfloor structure. The ACAP design exceeds the need for the civil rotorcraft crash environment; therefore, a method was established to interpolate lower levels of crash resistance from the ACAP upper bound.

The zero point of the curve was determined by a parametric analysis similar to the landing gear shear and moment analysis discussed in Section 3.1.1. The fuselage loads were sized until the maximum crash moment and normal flight moment were equal, which was determined to be the point where no crash penalty occurred. The zero point for ACAP came out to be approximately 5 to 6 ft/sec. The curve was sized proportionately to the square of the velocity between the zero point and 3.6 percent. To determine the specific weight penalty for another subfloor concept, the curve in Figure A-6 would have to be normalized by the ratio of specific energy absorption between the new design and the Kevlar/epoxy subfloor concept used in this study.

3.1.4 Fuselage Crush Loads

The final fuselage weight factor is that due to modifications to the fuselage structure to handle the moments exerted on the fuselage from subfloor crushing. The fuselage weight penalty associated with subfloor crushing loads was determined by subtracting other effects (landing gear and crush material) from the total weight penalty. Again, the ACAP was used as the principal data point of reference. The ACAP aircraft experienced a 170-lb change in weight in the basic fuselage due to the crash resistance design. This total minus the weights obtained for fuselage penalty due to the three other factors yielded the amount of weight penalty incurred in the fuselage due to the fuselage bending loads; this is the maximum point on the correlation shown in Figure A-7. The remainder of the curve was determined by gauging the curve proportionately to the square of the velocity, or energy, as the change in velocity approached zero.

®Kevlar is a registered trademark of E.I. Du Pont de Nemours & Co., Inc.

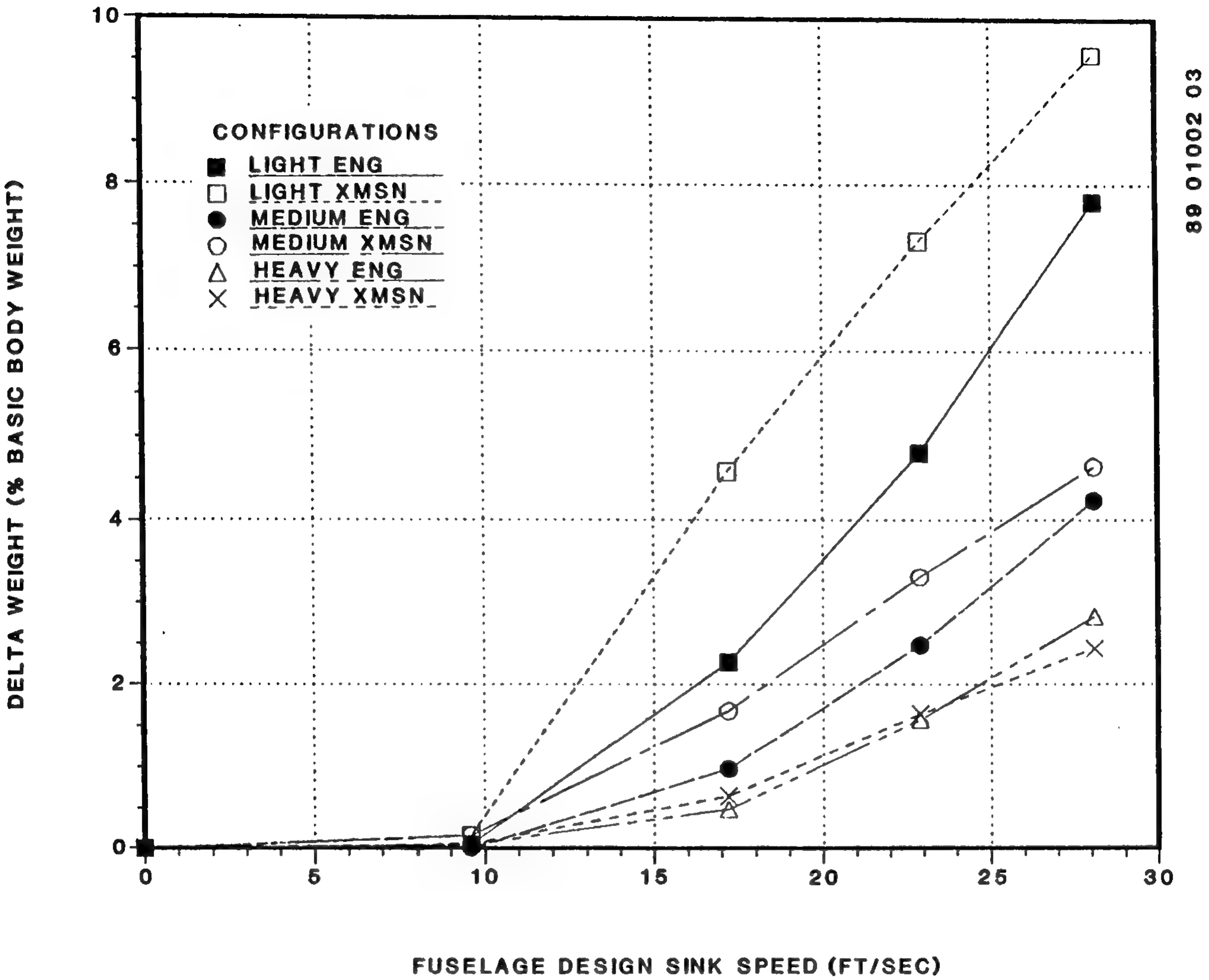

Figure A-5.
Fuselage weight increments from large mass retention requirements.

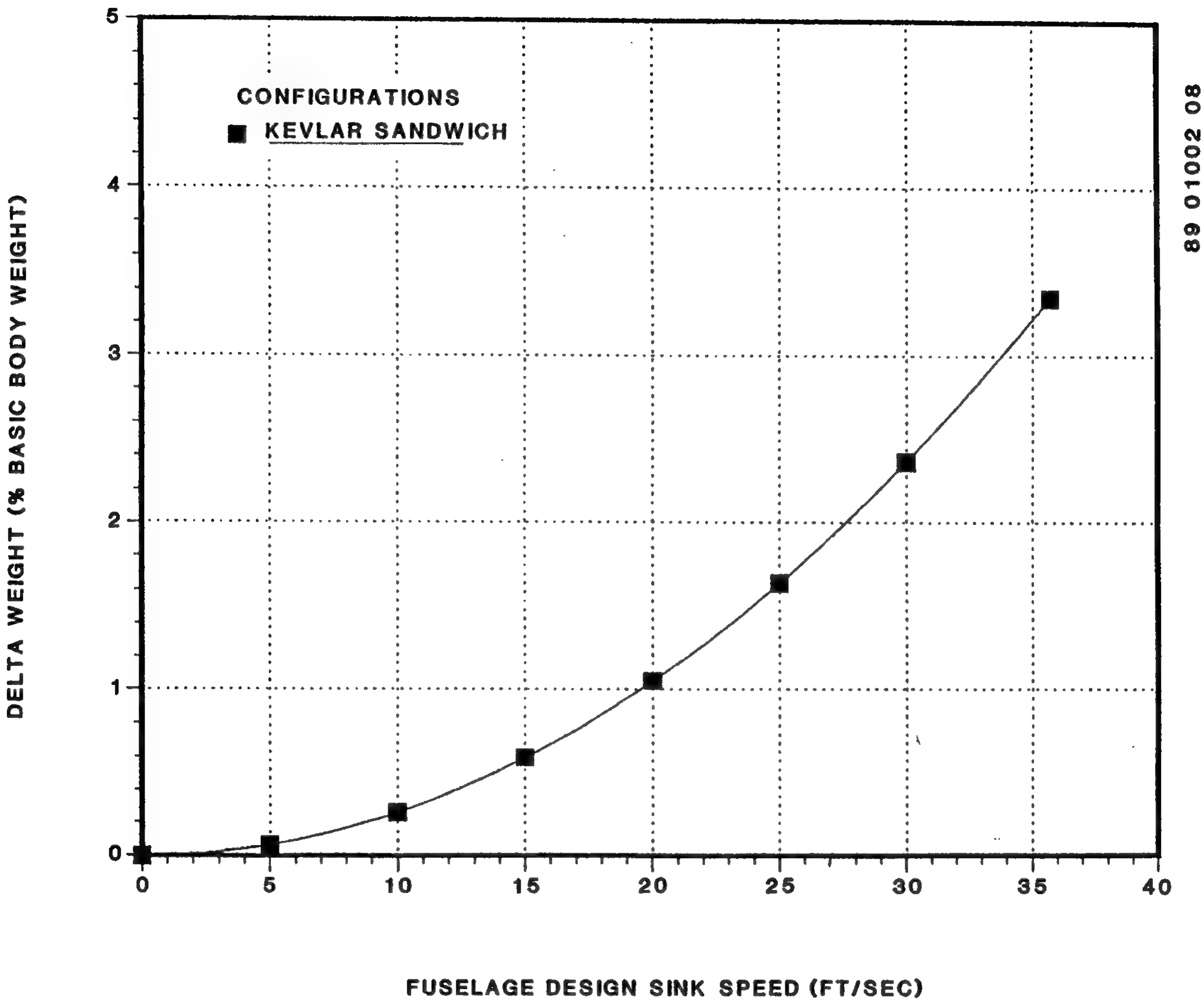

Figure A-6.
Fuselage weight increment from subfloor crush material.

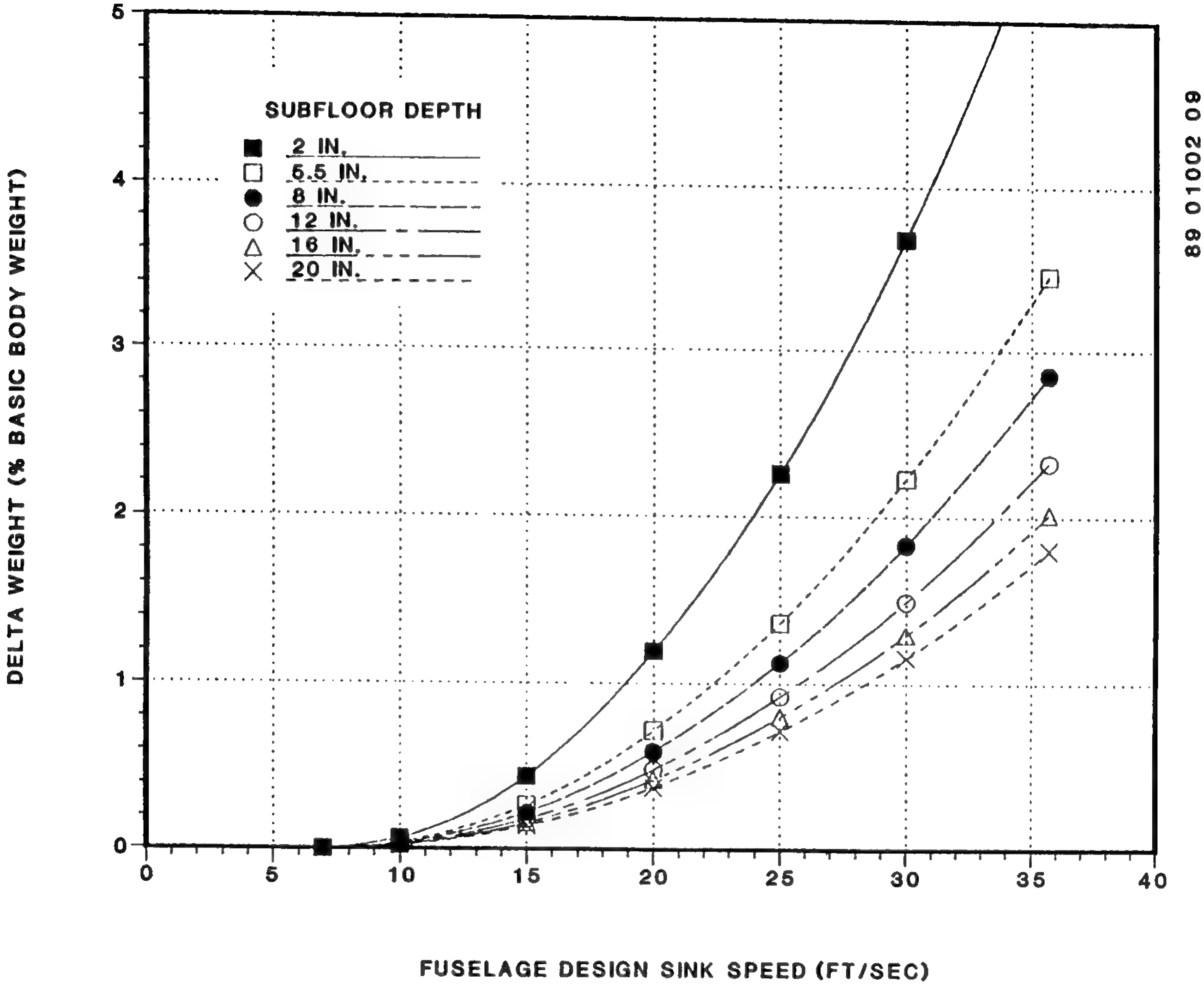

Figure A-7.
Fuselage weight increment from fuselage crush loads.

The resulting correlation for the weight penalty associated with fuselage crush loads indicates a range of 0 to 5 percent of BBW depending on the design sink speed and the available subfloor crush depth.

3.2 LANDING GEAR WEIGHT PENALTY ASSESSMENT

Preliminary estimates of landing gear weights were determined as a function of aircraft gross weight to establish the influence of adding various degrees of crash resistance. It should be noted that the relationship between landing gear weight and an aircraft weight parameter is much more closely correlated to gross weight than the BBW that was used for the fuselage weight penalties. Estimates of crash-resistant landing gear weight penalties were determined for the medium weight generic helicopter. The weight of a baseline landing gear with a reserve energy sink speed of 10.0 ft/sec was used as a basis for determining weight increase in percent of gross weight for providing crash attenuation for sink speeds ranging from 10.0 to 23 ft/sec. Weight penalties were calculated for a trailing arm and cantilevered wheel gear, and for a skid gear. Figure A-8 presents a comparison of the weight penalty correlation for fixed and retractable trailing arm landing gear, and for skid gear. The weight penalty correlation for the cantilevered landing gear are shown in Figure A-9.

Even though the landing gear weight penalties were calculated for the medium weight helicopter, previous BHTI design studies indicated that these correlations would apply to the range of light, medium, and heavy helicopters examined in this study.

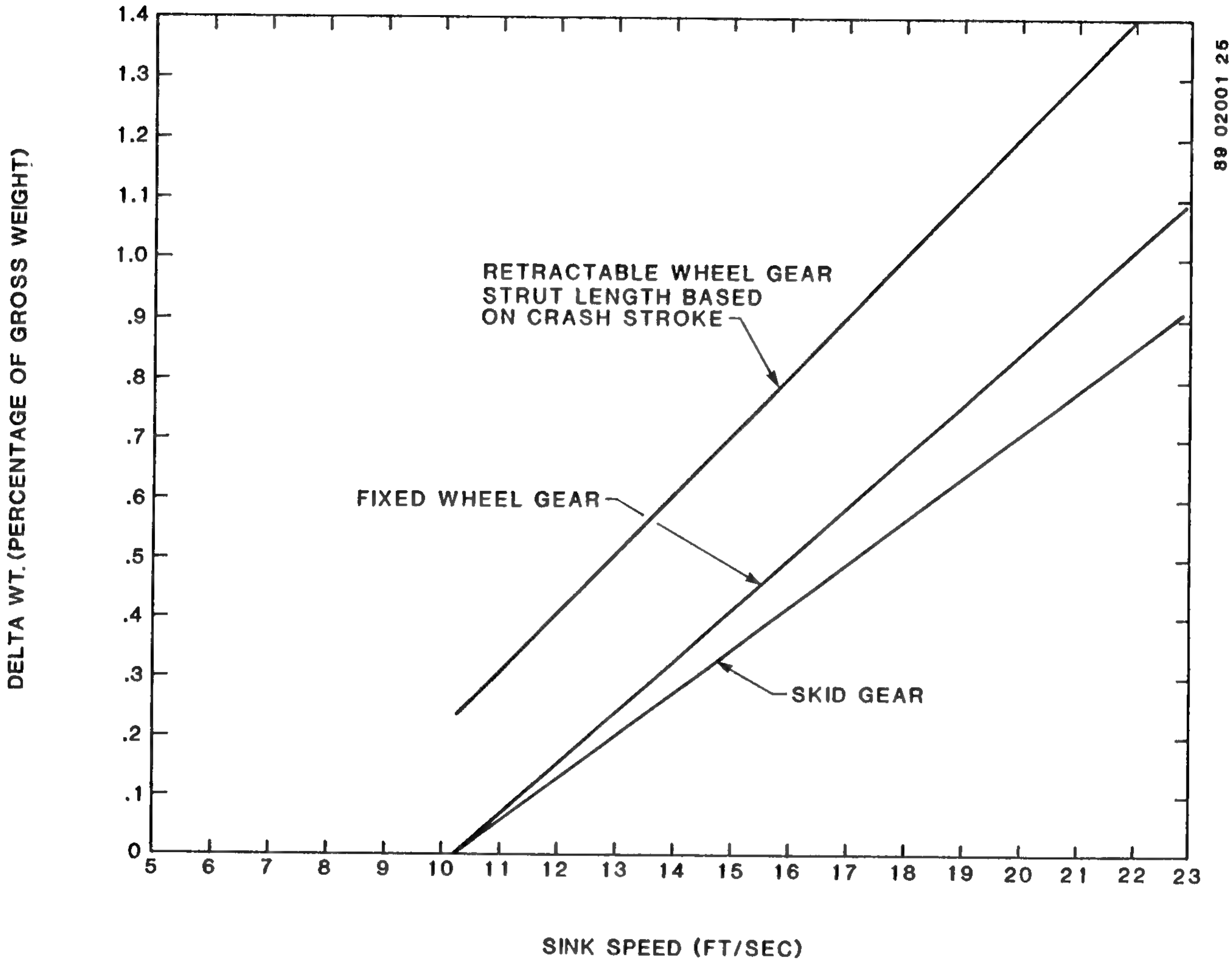

Figure A-8.
Gross weight increase due to crash attenuation for trailing arm wheel gear and skid gear.

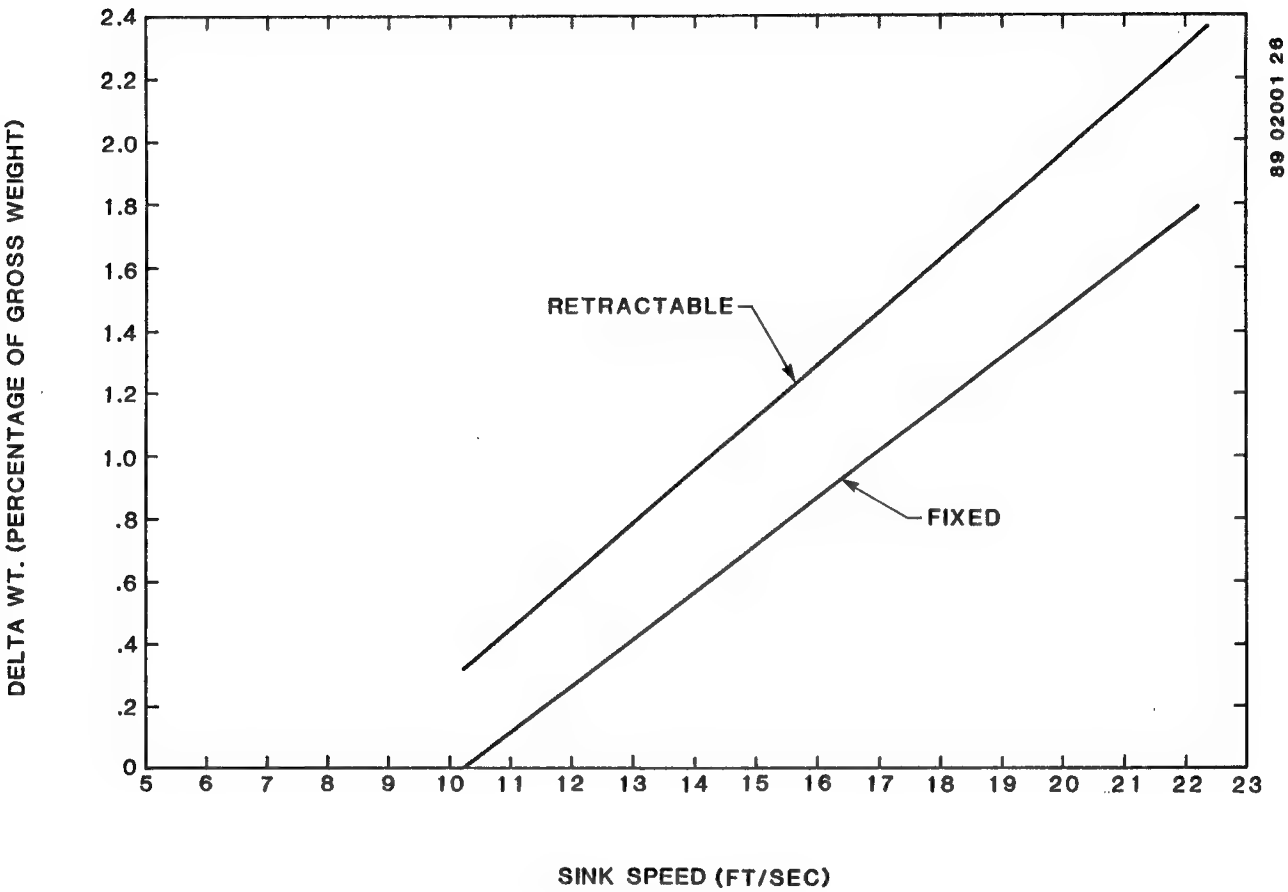

Figure A-9.
Gross weight increase due to crash attenuation for cantilevered wheel landing gear.

APPENDIX B

SUMMARY REPORT ON CRASH-RESISTANT FUEL SYSTEMS FOR CIVIL ROTORCRAFT

1.0 BACKGROUND

The analysis of civil helicopter accidents occurring between 1974 and 1978, which was reported in Analysis of Rotorcraft Crash Dynamics for Development of Improved Crashworthiness Design Criteria*, evaluated the effect of postcrash fire on occupant survival. It was noted that for almost any combination of horizontal and vertical impact velocities the chance of postcrash fire was significant. Postcrash fires occurred in 11 percent of survivable accidents, in 43 percent of partially survivable accidents, and in 52 percent of nonsurvivable accidents. The data contained in that report indicated that 14 percent of all injuries and fatalities in civil helicopter accidents were the result of postcrash fires. Postcrash fires were identified as the number one injury-producing hazard in this study.

Previous studies indicate that the postcrash fire hazard has not been limited to civil helicopters. Because of the high incidence of thermal injuries and fatalities, the U.S. Army committed significant resources to eliminating postcrash fires in their aircraft. All Army helicopters are now equipped with crash-resistant fuel systems (CRFS). The experience to date with these CRFS-equipped helicopters has been a 66-percent reduction in postcrash fires in survivable accidents and an 18-percent reduction in fires in nonsurvivable accidents. Of greater significance is the resultant 75-percent reduction in thermal injuries and the elimination of thermal fatalities in these survivable impact conditions. Although CRFS technology exists today in military aircraft and could be applied to civil helicopters, appropriate modifications to this technology must be made since the typical crash impact severity is lower for civil helicopters.

An evaluation was conducted of the CRFS technology that has proven successful in military helicopters. The primary approach used by the Army has been to prevent fuel spillage while minimizing potential ignition sources. In older helicopters already in service, the prevention of fuel spillage through the use of crash-resistant fuel cells was the principal approach taken since it was not always possible to eliminate ignition sources. In new helicopters, i.e. those designed from their inception to be crash resistant, both approaches of preventing fuel spillage and minimizing ignition sources were applied.

The approach used in this study to evaluate CRFS technology is very similar in concept, but not degree, to that used in the military systems. Both prevention of fuel spillage and minimization of ignition sources would be employed for civil rotorcraft. However, implementation of these two design goals results in different impacts on the aircraft design. Prevention of fuel spillage requires the incorporation of tougher, crash-tolerant components in the fuel system. This results in both a weight and cost impact. Minimization of potential ignition sources has a greater impact on the configuration and layout of the aircraft than on the ultimate cost and weight. This study concentrated on appropriate technology for fuel containment such that the impact on weight and cost could be quantified. Methods for elimination of potential ignition sources were not considered in detail; however, various concepts appropriate for civil rotorcraft can be found in the Aircraft Crash Survival Design Guide, Volumes I and V**.

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*Coltman, J. W., et al., Analysis of Rotorcraft Crash Dynamics for Development of Improved Crashworthiness Design Criteria, DOT/FAA/CT-85/11, U.S. Department of Transportation, Federal Aviation Administration, Technical Center, Atlantic City Airport, New Jersey, June 1985.

**Aircraft Crash Survival Design Guide, Volumes I-V, Simula Inc., Phoenix, Arizona; USARTL TR-79-22 A/E, Applied Technology Laboratory, U.S. Army Research and Technology Laboratories (AVRADCOM), Fort Eustis, Virginia, 1980.

The control of fuel spillage, even in accidents with significant structural damage, is predicated on:

- Containing the fuel in the fuel cells
- Preventing spillage from pulled and broken fuel lines by the use of self-sealing breakaway couplings/valves
- Preventing spillage through the vent lines during rollover or in any adverse postcrash attitude
- Use of a suction fuel feed system to prevent the continued pumping of fuel from a broken or separated fuel line.

If these principles can be employed in the design of a CRFS, the incidence of fuel spillage will be greatly reduced, which in turn will greatly reduce the chances of a postcrash fire. In those cases where a fire does occur, the fire intensity will be reduced, enhancing postcrash survival.

2.0 CRFS DESIGN PRINCIPLES

Fuel cell design is a critical element in the CRFS to contain the bulk of fuel during a crash. Successful military systems are fabricated from laminated rubberized nylon fabric resulting in a high strength fuel cell and are attached to the airframe with high-strength frangible fittings. To be qualified to military specification MIL-T-27422B, these fuel cells must not spill fuel when dropped from a height of 65 ft onto a flat concrete surface. Further, the material used in military fuel cells is often self-sealing to minimize fuel loss due to ballistic impact.

For civil helicopters, the use of fuel cells with a qualification drop test height of 50 ft has been recommended by the rotorcraft industry. It is believed that fuel cells capable of meeting this test condition would be appropriate for the lower civil crash impact conditions. Use of high-strength fabric and high-strength fittings similar to those used in the military fuel cells, but with lighter construction, should result in the same measure of postcrash fire control. The lighter construction is possible due to the lower impact requirements and the elimination of the ballistic tolerance requirement for the military cell material. Another available technology for civil use is multilayered elastomeric material for fuel cell construction. Because the material is highly elastomeric, with an elongation to failure of approximately 250 percent, the fuel cell fittings are not subjected to the same high loads as the high-strength fabric tanks. Thus, it is projected that the overall fuel cell weight would be reduced. However, lower cut and tear resistance of this material has not been fully validated for crash resistance.

Currently most fuel lines in civil helicopters are constructed of aluminum tubes and fittings. Such lines are easily broken when structural deformation occurs in crash impacts. To overcome this problem, the fuel lines should consist of flexible hose with a steel-braided outer sheath. When the lines are routed through areas of probable large displacement, self-sealing breakaway coupling/valves should be located as far as possible from probable impact areas and routed along the heavier structural members with attachment using frangible clamps. Self-sealing breakaway valves are used where the fuel lines pass through the firewalls that separate the engines from the airframe so that the line seals if the engine is displaced during a crash impact.

3.0 CRFS DESIGN CONFIGURATION FOR THE GENERIC ROTORCRAFT

The following general notes apply to the fuel system installation for all three generic civil rotorcraft designs. Specific features of the CRFS for each generic rotorcraft are discussed in the sections that follow.

1. Fuel system configuration is based on engine fuel inlet requirements. Fuel system specifications considered were: Federal Aviation Regulations (FAR) Parts 27 and 29, MIL-F-17874, and MIL-F-38363. The two basic fuel inlet configurations are:

   a. The engine can operate fully with negative fuel inlet pressures. Engine can handle fuel-vapor-to-liquid ratio (V/L) of approximately one (1).

      - An airframe boost pump is not required
      - An airframe filter is not required since the engine incorporates one
      - A fuel flow meter is not required since the engine has its own.

   b. The engine requires positive fuel inlet pressure.

      - Two airframe boost pumps are required (main and auxiliary)
      - An airframe fuel filter is required if the engine does not have one
      - A fuel flow meter is required if the engine does not have one.

   The baseline fuel system considered for each of the three generic rotorcraft assumes the engine requires positive fuel inlet pressure. The fuel systems can be simplified if the engine has negative fuel inlet pressure capability and a boost pump, fuel flow meter, and fuel filter with the engine. Only the basic fuel and fire extinguishing systems were considered. Components which were not considered in the fuel system included pressure sensors, temperature sensors, warning lights, pressure refueling, auxiliary tank, engine drain, lubrication, etc.

2. The following crash-resistant design concepts were used in the systems for the three generic rotorcraft.

   a. Use a suction engine feed system to keep pressurized fuel out of cabin/baggage compartments. In a suction system, air is pulled into a hole as opposed to fuel being sprayed out of it.

   b. Use an engine that has negative fuel inlet pressure capability with V/L = 1. If not, engine should have accessory pads that can drive boost pumps. Fuel filter, flow meter, and complete lubrication system should come with the engine.

   c. Route lines with an upward slope to engine and avoid horizontal runs and potential vapor traps.

d. If engine requires positive fuel inlet pressure, mount the boost pump, fuel filter, and fuel flow meter in the engine compartment. As a minimum, they should be outside the cabin/baggage compartments. Thus, the portion of the fuel system within the cabin/baggage compartment is a suction system. Pumps must have hot fuel capability.

e. Use breakaway valves following these guidelines:

- The minimum breakaway load for any valve should be 400 lb for a 1-in. valve and increase with the size of the valve to a minimum of 800 lb for a 2-in. valve.

- Use high-strength hose, not tubing, to actuate the breakaway valve. Hose must have a strength of at least two times the minimum valve breakaway load.

- Avoid preloading breakaway valve during installation.

- Ideally, there should be no external leakage when the breakaway valve is partially separated.

f. Use a fuel cell following these guidelines:

- Avoid inside corners; they can prevent cell movement during a crash, resulting in a torn cell.

- Avoid a cube-shape cell. A low, flat cell will produce less fabric stress in the drop test, resulting in less fuel cell weight.

- Avoid fittings in the side walls of the cell, as they will require reinforcement that will add weight to the cell. If a fitting must be in the side wall, locate it as high as possible. This will minimize the increase in cell weight.

- When installing the fuel cell, frangibly attach the access cover, fuel quantity tank unit, sump drain valve, filler cap, etc., to structure. The load required to break the frangible attachment should not be greater than half the strength of the cell or fitting.

g. Route lines following these guidelines:

- Avoid running lines under the floor. Lines between floor and bottom of aircraft are most vulnerable in a crash.

- Route lines close to heavy structural members to take advantage of their protection.

3.1 CRFS DESIGNS FOR THE GENERIC LIGHT ROTORCRAFT

Three CRFS designs were examined for the light generic rotorcraft. The first system was designed to meet FAR Part 27 requirements and to establish a baseline fuel system weight for the aircraft. The other two designs used the CRFS principles discussed above. These two systems differ in that one used two separate fuel cells and one used a large single cell.

The two-cell system has the advantage of minimizing the movement of the aircraft center-of-gravity (c.g.) as the fuel is used. The single-cell system achieves lower weight and complexity, while meeting the CRFS requirement.

As noted above, the basic fuel system was designed to meet FAR Part 27 requirements. This non-crash-resistant system consists of two lightweight, bladder-type cells supplying fuel to one engine via tank-mounted fuel pumps and aluminum alloy tube fuel lines. Two fuel cells were used to minimize center-of-gravity movement as fuel is used. To make the most of the limited available space, the aft fuel cell was used to support the seat cushions for the three cabin occupants (i.e., no space was left for energy-absorbing seating in the cabin area).

The second fuel system was the two-cell CRFS design. Main and auxiliary fuel pumps were mounted on or close to the engine to create a suction feed system. The system maintained a two-cell configuration but the aft fuel cell was of a new geometry compared to the baseline. The cell no longer protrudes forward under the passengers and has a simpler configuration. The benefits of this change are twofold: (1) removal of the cell from under the seats provides space for energy absorption, and (2) the fuel cell re-entrant corner is eliminated, which significantly enhances its capability to displace within its structure without rupture. The fuel hoses and vent lines were equipped with self-sealing breakaway valves at their exits from the cells and at the firewall. The fuel tanks were also equipped with fuel quantity probes with a rounded shoe at the end so that they collapse rather than penetrate the fuel cell when crushed.

The final fuel system design demonstrated the simplicity of a single-cell system when compared with the two-cell design. This system would be preferred if the center-of-gravity excursion could be maintained within the design limits of the helicopter. Two breakaway valves were used in the fuel line and two were used in the vent lines.

3.2 CRFS DESIGNS FOR THE GENERIC MEDIUM ROTORCRAFT

The baseline fuel system was designed to meet FAR Part 29 requirements. The fuel is contained in two main fuel cells within the aft fuselage and in two smaller fuel cells in the outboard sponsons. Each of the two engines is fed fuel from one main tank, but a cross-feed line allows fuel to be supplied to either or both engines from either of the two main tanks. As fuel is used from the main tanks, the fuel may be transferred from the sponson tanks by low-pressure transfer pumps mounted in the sponson tanks. The main fuel cells for the basic system extend under the aft cabin seats and also support the back cushions for those seats.

A single CRFS design was examined for the medium generic rotorcraft. The main fuel cells were reshaped to remove the fuel from under the aft cabin seats and to eliminate the re-entrant corner of the cell, making their shape more rectangular and thus more crash resistant. Positioning the main and auxiliary fuel pumps near the engine rather than in the fuel cells themselves changed the system to a suction feed with fuel available for each engine from one main and one sponson cell. Cross-feed lines with integral check valves allowed fuel to be

supplied to either engine from all four fuel cells. Breakaway valves were installed in the fuel lines and vent lines in the following places: where they exited the fuel cells, where the main fuel lines passed through the fuselage structure, at the engine firewalls, and in each cross-feed fuel line.

3.3 CRFS DESIGNS FOR THE GENERIC HEAVY ROTORCRAFT

The baseline fuel system is a non-crash-resistant system consisting of two lightweight, bladder-type fuel cells, each supplying fuel to one of two engines via tank-mounted fuel pumps. Aluminum alloy tube fuel lines are used, and a cross-feed line is incorporated to allow fuel from either tank to fuel either engine. As in the light helicopter design, two fuel cells were used to minimize c.g. movement. The fuel cells project into the forward and aft rows of passenger seats. This positioning makes good use of the available cabin space with the fuel tank structure supporting the seat back and bottom cushions, and the lap belt restraints.

The CRFS for this helicopter maintains the same two-cell configuration but the fuel cell configuration is modified so that they no longer protrude under the passenger seats. This installation permits the use of load-attenuating seats and improves the crash resistance of the fuel cell itself by removing the re-entrant corner. The main and auxiliary fuel pumps are mounted on or close to the engines to create a suction feed system. The fuel cell hoses and vent lines are equipped with self-sealing breakaway valves at their exits from the cells, at the engine bay firewalls, and in each cross-feed line. Collapsible fuel quantity probes are installed in each fuel cell.

4.0 DESIGN DETAILS FOR GENERIC ROTORCRAFT CRFS DESIGNS

4.1 DESIGN DETAIL OF FUEL CELLS

Typical data supplied by fuel cell manufacturers included sketches of the fuel cell with access cover, filler opening, vent line, and fuel quantity probe fittings and the sump valve/tank drain locations. Concepts from FPT, Inc. are shown in Figure B-1. This figure shows the typical fitting construction using molded fittings for both the flexible and crash-resistant type constructions.

4.2 DESIGN DETAILS FOR FUEL/VENT LINE HOSES

Typical hose construction is that of the Stratoflex 156 medium pressure hose which has an inner tube of seamless elastomeric compound, reinforced with one-and-a-half braids of stainless steel wire. Where required, a firesleeve cover consisting of one layer of fiberglass braid with a bonded seamless extruded silicone rubber cover may be added. The hose may be used with straight, 45-degree, or 90-degree elbow flareless fittings. A typical hose assembly is shown in Figure B-2.

4.3 DESIGN DETAILS FOR SELF-SEALING BREAKAWAY VALVES

A typical design for a self-sealing breakaway valve is shown in Figure B-3. Spring-loaded balls that rotate to close off the fuel flow are installed on each side of the frangible valve section. The fuel flow through the valve balls results in negligible pressure drop, especially important in a suction fuel system. The valves have indicators that show whether the ball valves are open or have rotated to the closed position.

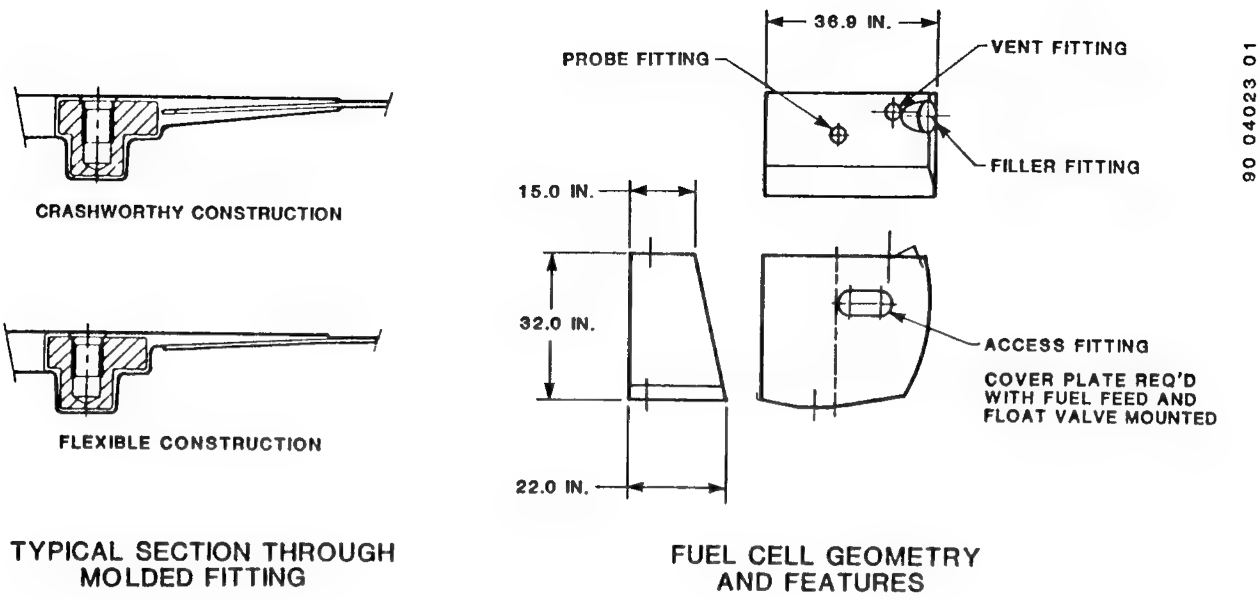

Figure B-1.
Typical fuel cell design details.

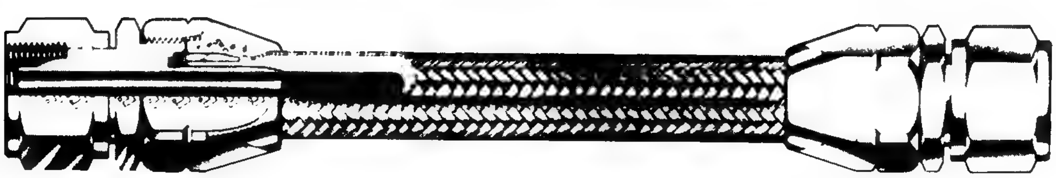

Figure B-2.
Typical hose construction.

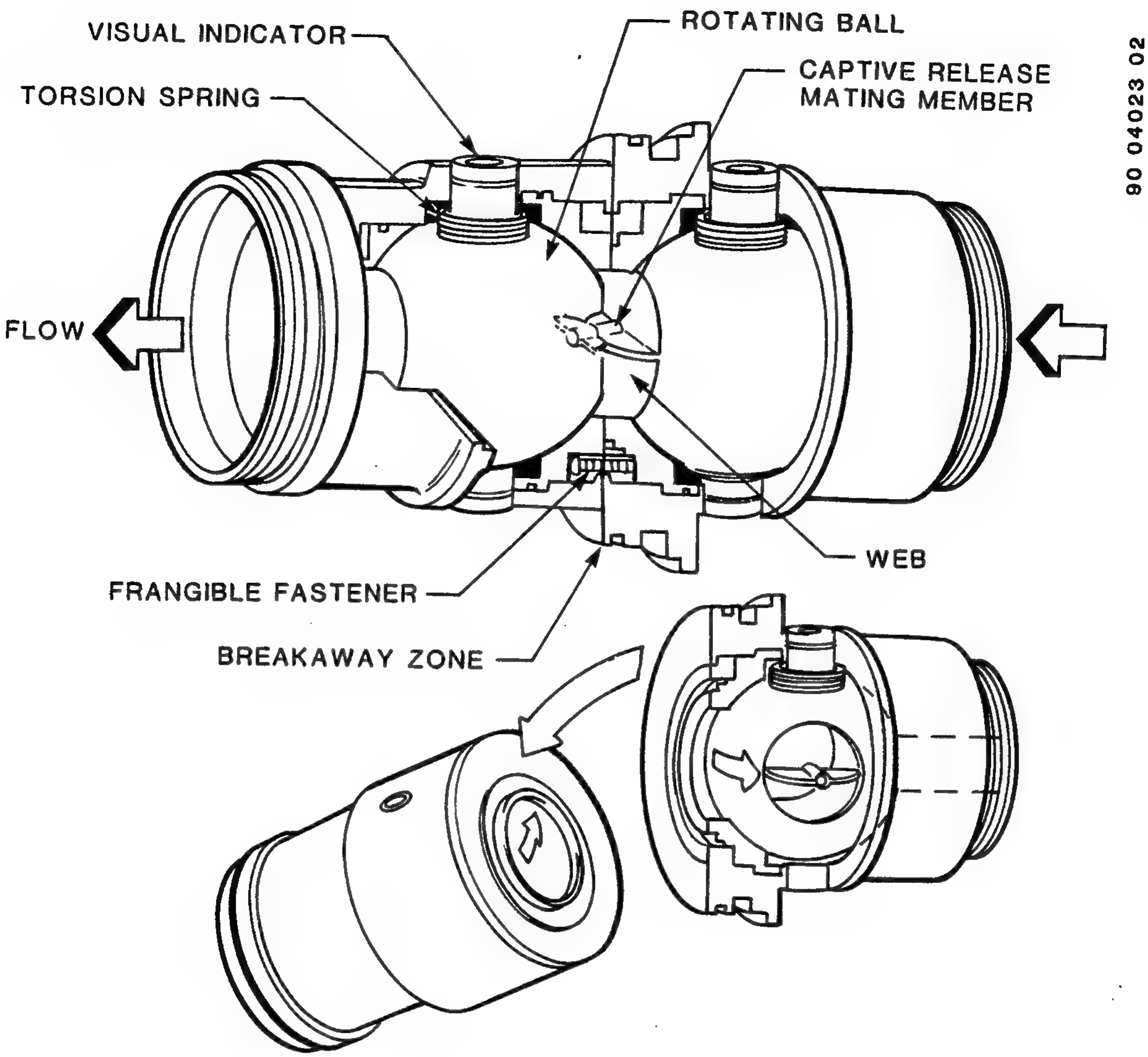

Figure B-3.
Typical self-sealing breakaway valve.

5.0 WEIGHT AND COST ANALYSIS FOR CIVIL CRFS

5.1 SOURCES OF DATA

Weight and cost data were provided by the following manufacturers of fuel cells, fuel lines, and self-sealing breakaway valves:

Fuel cells:

Uniroyal Plastics Company, Inc.
Engineered Systems Department
312 North Hill Street
P.O. Box 2000
Mishawaka, IN 46544-1399

AM Fuel
P.O. Box 887
Magnolia, AR 71753

FPT, Inc.
106 Magnolia Drive
Wilmington, NC 28403

Loral Engineered Fabrics
669 Goodyear Street
Rockmart, GA 30153-2417

Fuel Lines and Breakaway Valves:

Spectrum Associates Inc.
179 North Broad Street
Milford, CT 06460

Symetrics, Inc.
3353 Old Conejo Road
P.O. Box 555
Newbury Park, CA 91320

Aeroquip Corporation
Aerospace Division
300 South East Avenue
Jackson, MI 49203-1972

The data supplied by the manufacturers included the recurring cost per shipset of fuel cells, fuel lines, and breakaway valves based on a production rate of 100 shipsets per year for a period of five years, exclusive of packaging and shipping. Costs were estimated in 1989 dollars. All the weight and cost data were based on the use of fuel lines, vent lines, and self-sealing breakaway valves with a 1-in. inside diameter.

5.2 FUEL CELL WEIGHT AND COST ESTIMATES

Weight and cost increases were determined for each of the three generic rotorcraft designs. The increases were determined as the difference between the baseline fuel system and the CRFS selected for the aircraft. For the light generic rotorcraft, the weight and cost of the simpler single-cell system were used to calculate weight and cost increases.

The weight and cost data from the four fuel cell manufacturers were reviewed to determine the approximate weight and cost increase. The increases for each of the three generic helicopters is based on the average of increases from three of the four manufacturers. The results are shown in Table B-1.

Table B-1.
Fuel cell weight and cost increase

Generic Civil Helicopter Weight Class	Estimated Weight Increase per Aircraft (lb)	Estimated Cost Increase per Aircraft ($)
Light	21.5	2,140
Medium	34.3	2,400
Heavy	34.0	1,250

5.3 FUEL LINE, VENT LINE, AND BREAKAWAY VALVE WEIGHT AND COST ESTIMATES

The weight and cost data from two manufacturers of fuel and vent line hoses, valves, and fittings were used to estimate the weight and cost increase to incorporate crash-resistant fuel and vent lines. The weight and cost data from three manufacturers of self-sealing breakaway valves were used to estimate the weight and cost increase to install these valves. The results for the three rotorcraft designs are shown in Table B-2.

Table B-2.
Fuel line, vent line, and breakaway valve weight and cost increases

Generic Civil Helicopter Weight Class	Estimated Weight Increase per Aircraft (lb)	Estimated Cost Increase per Aircraft ($)
Light		
Lines	10.2	380
Valves (8)	7.6	3,720
Medium		
Lines	22.4	620
Valves (16)	15.2	7,040
Heavy		
Lines	26.1	578
Valves (10)	9.5	4,550

5.4 TOTAL CRFS WEIGHT AND COST ESTIMATES

The fuel cell and fuel line data were combined to develop a total cost and weight estimate for each CRFS design. The total system cost and weight increases are shown in Table B-3. It is interesting to note that the cost increases for the light and heavy rotorcraft are very similar. However, the complex four-cell system for the medium generic rotorcraft is costly in terms of both weight and price.

Table B-3.
Total system weight and cost increases

Generic Civil Helicopter Weight Class	Estimated Weight Increase per Aircraft (lb)	Estimated Cost Increase per Aircraft ($)
Light	39.3	6,240
Medium	71.9	10,060
Heavy	69.6	6,378

6.0 SUMMARY

The following observations were made during the development of the CRFS designs for the three generic rotorcraft:

- The weight increases, regardless of weight class, are distributed approximately half to the fuel cells, one third to the fuel and vent lines, and one-sixth to the breakaway valves.

- The fuel cell weight increases are related to both the number and volumes of the tanks, and the number of fittings in the tanks; thus, large systems with fewer tanks have much less weight increase per gallon of fuel.

- The number of breakaway valves increases with the number of fuel cells and number of engines. The following data are representative of the three generic rotorcraft designs.

No. of Engines	No. of Cells	No. of Valves
1	2	8
2	2	10
2	4	16

- The cost increases, almost regardless of weight class, are due two-thirds to the installation of the breakaway valves, one-quarter to the fuel cells, and one-twelfth to the fuel and vent lines.

- Simple systems minimize weight and cost increases; system complexity such as the four-cell system for the medium helicopter results in weight and cost increases similar to those of the two-cell system for the >12,500-lb class helicopter. However, the fuel volume for the medium helicopter is only 254 gallons compared with 380 gallons for the larger helicopter.

APPENDIX C

SUMMARY REPORT ON CRASH-RESISTANT SEATING SYSTEMS FOR CIVIL ROTORCRAFT

1.0 BACKGROUND

Energy-absorbing seating systems are a critical element in the overall design of crash-resistant aircraft. Each of the major elements of the energy management system (landing gear, subfloor, and energy-absorbing seats) performs a function in absorbing vertical impact energy. Typically, the landing gear absorb energy prior to fuselage contact in a crash, decelerating the fuselage at a relatively low G-level. Subsequently, the fuselage impacts the ground and decelerates the fuselage at higher G-levels. The G-levels associated with fuselage crushing are typically much higher than the injury threshold for humans. Energy-absorbing seats are used to reduce the G-load transmitted to the seated occupant, which reduces the chance of spinal compression injury. Figure C-1 shows a simple example of G-loads associated with the various energy management components during a crash.

An energy-absorbing seat provides a lower acceleration to the occupant, causing the occupant to come to rest over a longer distance and time than the fuselage does. The difference between the stopping distance of the fuselage and seat results in relative motion called seat stroke. In the design of an energy-absorbing seat, the available stroke distance is a primary design factor. The necessary stroking distance is a direct function of the vertical velocity change that the fuselage will sustain and the G-level at which the subfloor crushes.

Even though seat stroke is a primary design factor for the configuration of an energy-absorbing seat, it has a relatively small effect on seat weight. The energy absorption devices on a stroking seat that limit transmitted load to the occupant also limit internal loads in the seat structure. Thus, the design loads for seat components only increase by a small amount as available seat stroke distance increases. However, there is a strong correlation between the maximum internal seat loads (and hence structural weight) and the forward or lateral occupant retention strength. Typically, the forward G-load for occupant retention is the primary factor in determining seat weight.

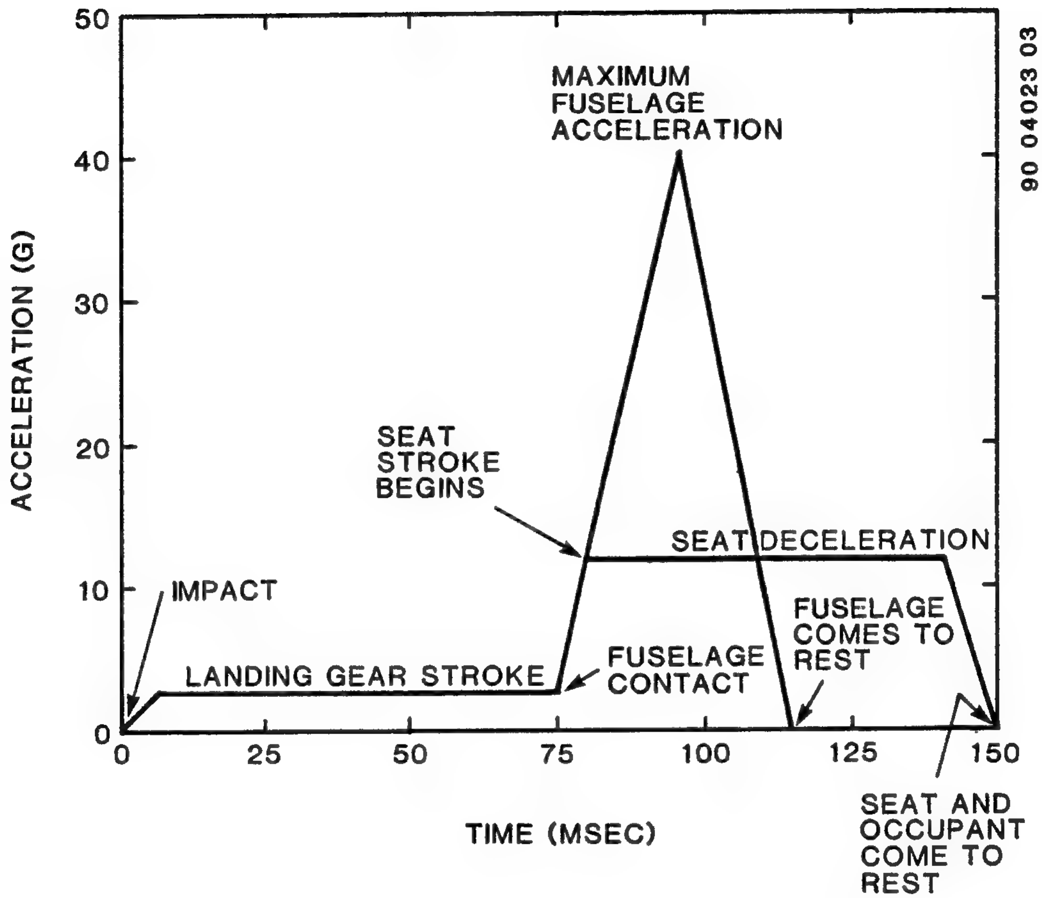

Figure C-1.
Simplified example of acceleration time-history for the three major energy management components.

2.0 ANALYSIS OF CRASH-RESISTANT SEAT PERFORMANCE

This section identifies five specific design levels for crash-resistant seats by defining the vertical, longitudinal, and lateral capabilities. Parametric correlations relate seat stroke and seat weight to these five impact levels. The parametric correlations were used in Section 6.0 of the main report for the trade-off analysis.

2.1 SEAT DESIGN LEVELS

Five design levels were established for a parametric study of seat design. The five levels were correlated with the five aircraft sink speed levels used for the airframe analysis described in Appendix A. The five levels correspond to sink speeds of 10.0, 14.0. 20.0, 26.0, and 32.0 ft/sec. These five sink speed levels were designated I through V for the analysis described in this section.

2.2 SEAT PERFORMANCE PARAMETRIC CORRELATION

A direct relationship exists between aircraft sink speed (vertical impact velocity) and required seat stroke to safely decelerate an occupant. For this analysis, a 170-lb occupant and an 11-G energy absorber limit-load were selected for calculation of seat stroke. The fuselage deceleration was assumed to be triangular with the peak acceleration and pulse duration typical of those measured in crash tests. Figure C-2 shows the relationship between aircraft vertical impact velocity and seat stroke derived from testing of a number of seat types at various test facilities and with various types of anthropomorphic dummies. As this correlation shows, no seat stroke is required for vertical impact velocities below approximately 14 ft/sec. However, as vertical impact velocity increases, the required seat stroke also increases. For example, at 26 ft/sec, which is close to the recently enacted dynamic test requirement for rotorcraft seats, approximately 5 in. of stroke is required.

Typical design practice has resulted in a relationship between vertical impact velocity and the forward retention strength for seats. These design practices were established based on proportionally increasing the levels of crash protection in the vertical, longitudinal, and lateral levels. Based on analysis of various seats and aircraft, seat retention strength can be related to vertical impact velocity as shown in Figure C-3. The forward load factor shown in Figure C-3 is based on static loading and a 170-lb occupant. The five impact levels used in the parametric study are shown on the graph. The lateral load factor for seat design also has a relationship to vertical impact velocity for rotorcraft based on design practice; Figure C-4 shows this relationship. Table C-1 summarizes the results of the parametric correlations which related seat stroke, forward retention strength, and lateral retention strength to the five impact levels.

The primary goal of the parametric analysis was to establish seat weight (and hence weight penalty) for various levels of crash resistance. Eighteen actual seat designs from various manufacturers were examined in detail to determine their weight and crash resistance performance levels. Emphasis was placed on seats with documented performance under dynamic test conditions. Figure C-5 shows the relationship between seat weight and forward load factor for the 18 seats evaluated. It should be noted that seat weights were adjusted to be consistent with a 170-lb occupant if the seats were nominally designed for another occupant weight.

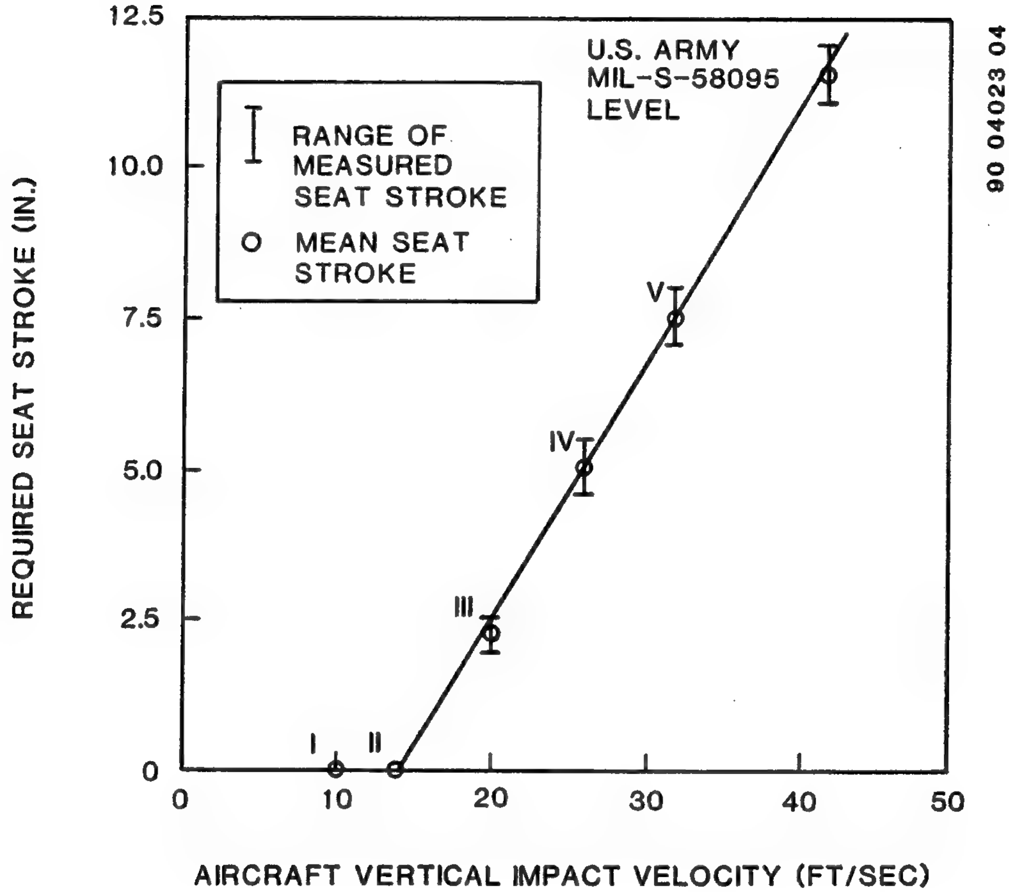

Figure C-2.
Relationship of seat stroke to aircraft vertical impact velocity.

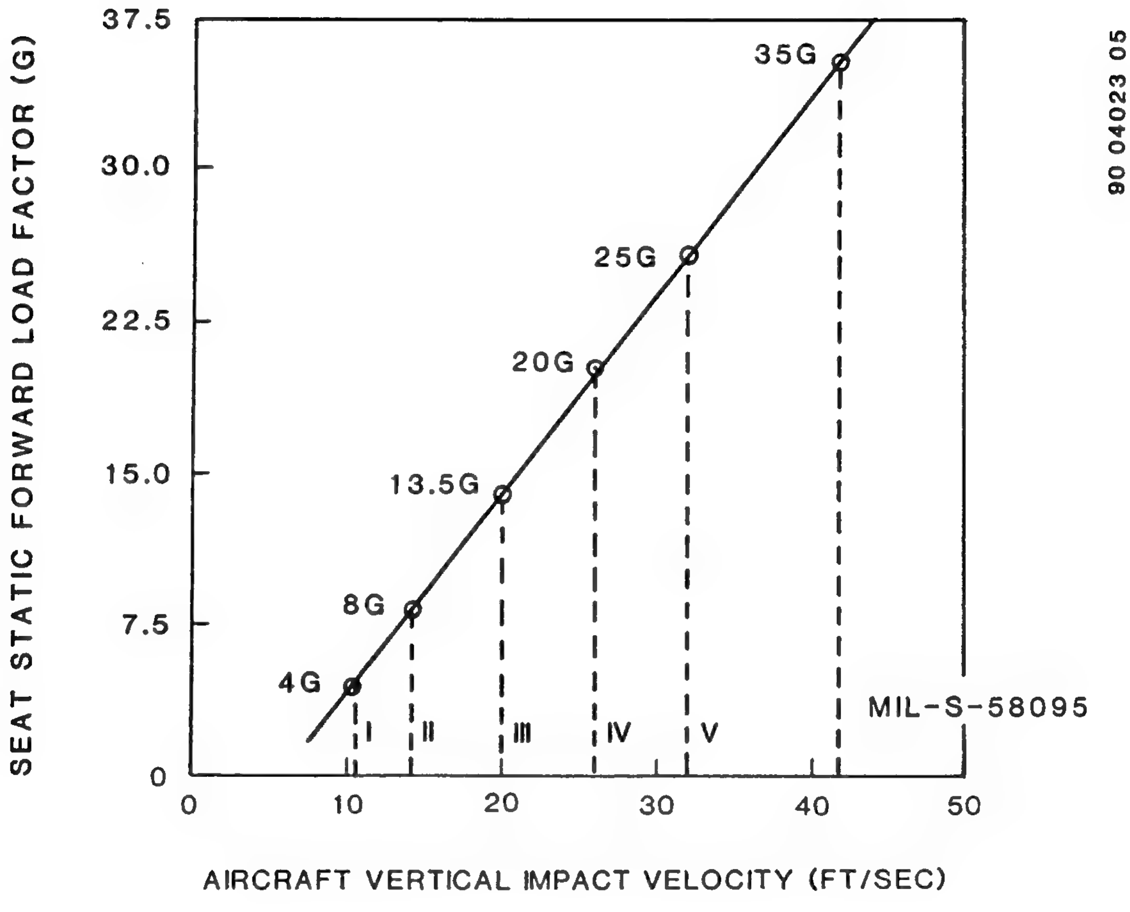

Figure C-3.
Relationship between aircraft vertical impact velocity and forward load factor for seat design.

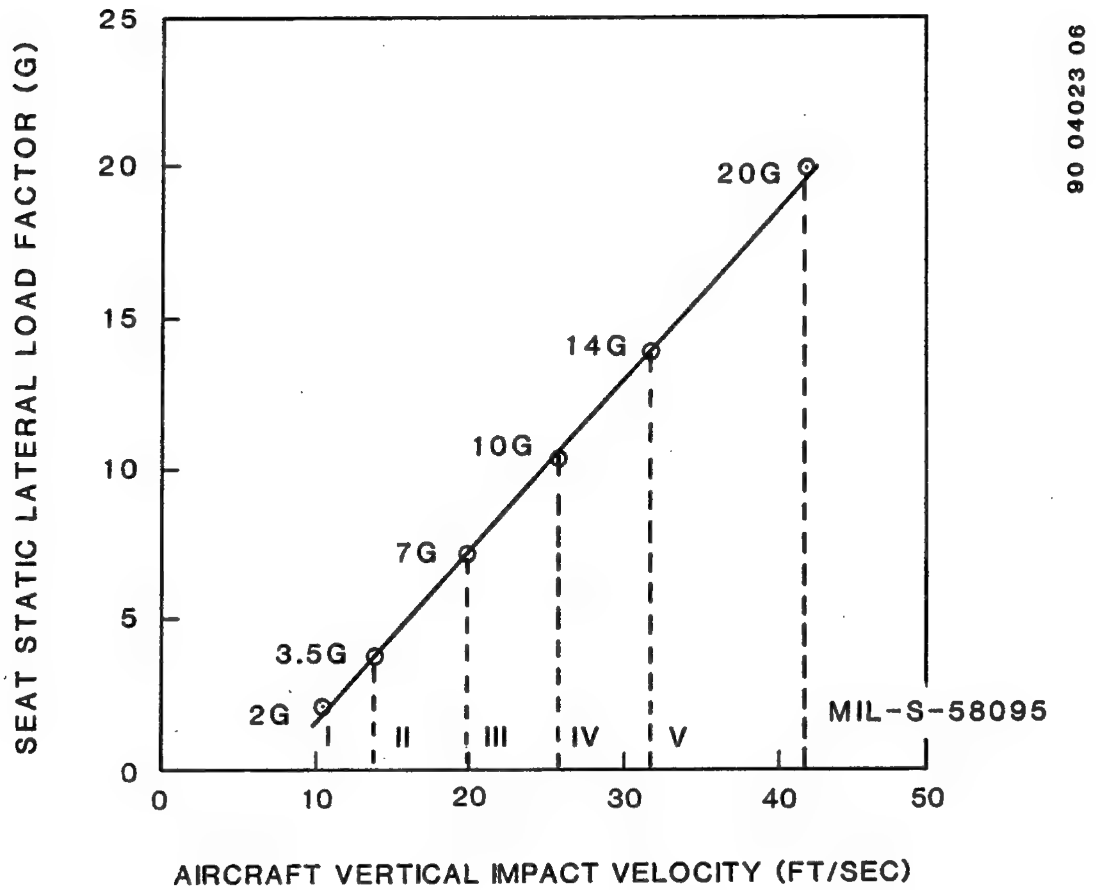

Figure C-4.
Relationship between aircraft vertical impact velocity and lateral load factor for seat design.

Table C-1.
Seat design parameters for five impact levels
used in seat parametric analysis

Impact Level	Aircraft Vertical Impact Velocity (ft/sec)	Seat Criteria: Vertical Stroke Distance (in.)	Seat Criteria: Forward Load Factor (G)	Seat Criteria: Lateral Load Factor (G)
I	10.23	0	4	2
II	14.0	0	8	3.5
III	20.0	2 - 2.5	13.5	7
IV	26.0	4.5 - 5.5	20	10
V	32.0	7 - 8	25	14
MIL-S-58095*	42.0	11 - 12	35	20

*The U.S. Army requirement is shown for reference only.

In Figure C-5 two linear approximations are shown for the correlation of seat weight to forward load factor. The upper line represents Type B seats which are freestanding, floor-mounted seats with lap belt and shoulder harness attached to the seat. The seat structure in Type B seats sustains the entire occupant inertial loading in a crash and, thus, requires the heaviest seat structure. The weight of Type B seats in Figure C-5 also includes cushions and typical upholstery for a utility configuration. The lower trend line in Figure C-5 represents the correlation of weight to forward load factor for Type A, C, and D seats. The definitions of these three seat types are listed in Figure C-5. These three types of seats were grouped together because they share a common design feature: the primary occupant restraint loads are transmitted directly to aircraft structure through the restraint system, thereby significantly reducing the seat structural requirements. In fact, many of the Type A, C, and D seats shown in Figure C-5 have restraint systems which are on the airframe itself. The effective weights shown in Figure C-5 for Type A, C, and D seats do not include restraint system weights; however, they do include cushion and upholstery weights.

The correlations shown in Figure C-5 were used to calculate seat weight for the five parametric impact levels (i.e., Levels I through V). The nominal weights for Types A, C, and D seats and for Type B seats are listed in Table C-2 at the five impact levels and, for reference, at the U.S. Army requirements contained in MIL-S-58095. A weight increment for higher crash resistance loads was then calculated as the difference between the baseline Level I seat weight and the higher impact level seat weight. It should be noted that the baseline Level I condition corresponds with a seat design complying with TSO-C39b.

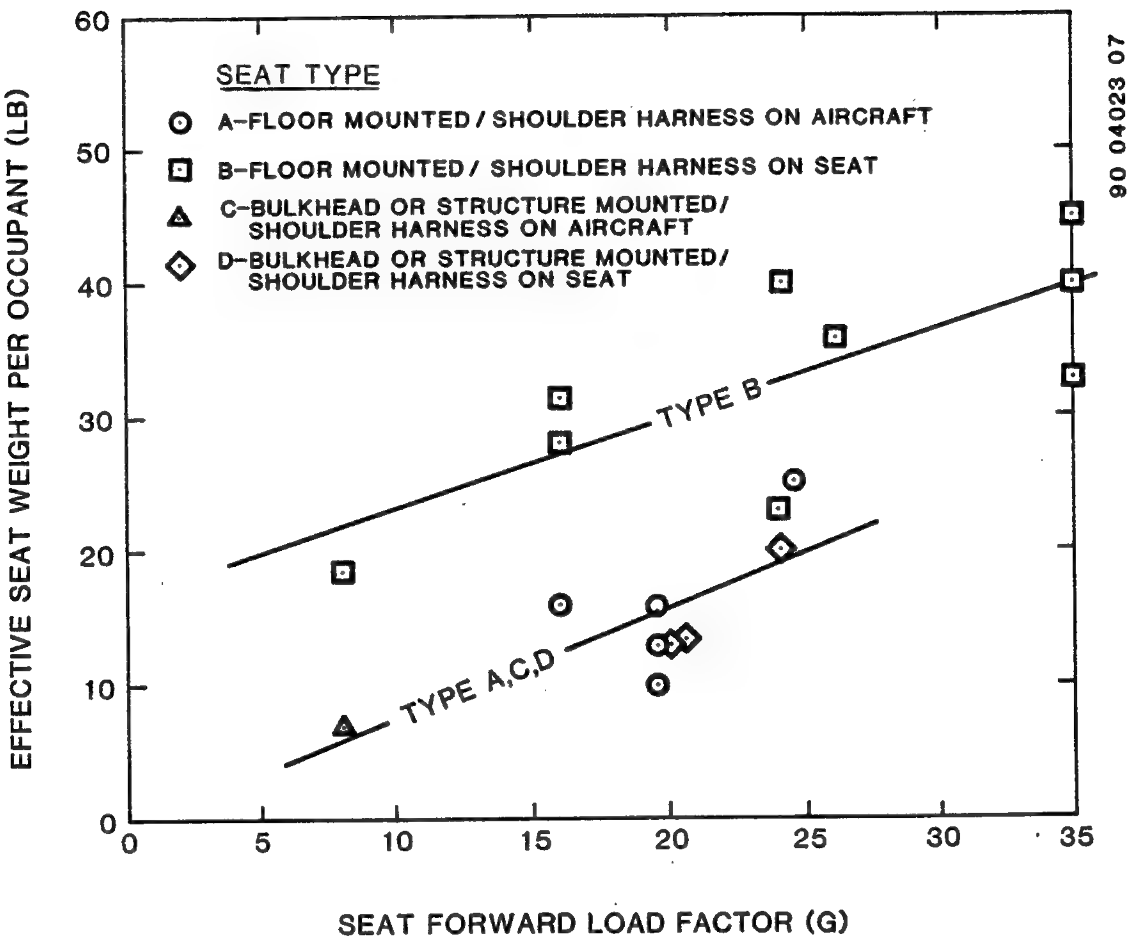

Figure C-5.
Correlation between seat weight and forward load factor.

The data presented in Table C-2 for Type A, C, and D seats show a very low baseline seat weight of 2.3 lb. Some explanation is required for this baseline seat. At impact Level I, the seat is not required to have vertical energy absorption and must sustain 4.0 G in the forward direction and 2.0 G in the lateral direction. However, for Type A, C, and D seats the occupant restraining loads are transmitted directly to the aircraft structure. The 2.3-lb baseline weight does not include restraint system weight (a typical restraint system including lap belt and shoulder harness would weigh approximately 3 to 4 lb). Therefore, the 2.3-lb weight is essentially a cushion with upholstery mounted on existing airframe structure. In contrast, the weight of a baseline Type B freestanding seat is estimated at 19.2 lb. The Type B seat weight includes seat, restraint system, cushions, and basic upholstery. The load path for the occupant restraint loads in the Type B seat is through the seat structure itself.

Table C-2.
Seat weight increment for increased crash tolerance
(based on design for a 170-lb occupant)

Impact Level	Type A,C,D Seats(1) Nominal Seat Weight(3) (lb)	Type A,C,D Seats(1) Weight Increment (lb)	Type B Seats (1) Nominal Seat Weight(4) (lb)	Type B Seats (1) Weight Increment (lb)
I (Baseline)	2.3	0	19.2	0
II	5.7	3.4	21.9	2.7
III	10.4	8.1	25.5	6.3
IV	15.9	13.6	29.8	10.6
V	20.2	17.9	33.1	13.9
MIL-S-58095(2)	28.6	26.3	39.7	20.5

(1) See Figure C-5 for seat type designation.
(2) The U.S. Army requirement is shown for reference only.
(3) Weight includes seat structure, cushions, and upholstery. Restraint system weight not included.
(4) Weight includes seat structure, cushions, upholstery, and restraint system.

As shown in Table C-2, the weight increment for increased seat crash resistance is higher for the Type A, C, and D seats than for the Type B seats. The higher weight increase for Type A, C, and D seats is associated with providing seat structure to permit vertical energy absorption. However, for freestanding Type B seats there is a basic seat structure already existing in the baseline seat, which is more readily adapted to include energy absorption.

3.0 SURVEY OF CANDIDATE CRASH-RESISTANT CIVIL ROTORCRAFT SEATS

A survey identified 12 seat design concepts that were considered to be candidates for civil rotorcraft. These 12 seat concepts were based on existing seat designs defined in published literature or experimental designs developed by Simula Inc. for various applications. Three seat attachment methods were considered in selecting the candidate seat concepts: freestanding, ceiling attached, and bulkhead mounted. A group of seat design engineers examined the strengths and weaknesses of each design concept. Nine factors were used in examining each of the seat concepts. The nine factors were:

- Weight
- Vertical energy absorption
- Longitudinal strength
- Lateral strength
- Attachment reaction loads/deformation
- Installation/removal
- Stowability
- Relative cost
- Secondary hazards.

These nine factors were used to assess the relative merits of each seat design concept for civil rotorcraft. The most promising concepts were selected and modified for use in the three generic rotorcraft models described in Section 4.0. Schematic drawings of each of the 12 seat concepts are presented here. Figures C-6 through C-10 show freestanding seat concepts. Figures C-11 through C-15 are seat concepts with ceiling attachments, and Figures C-16 and C-17 identify bulkhead-mounted concepts.

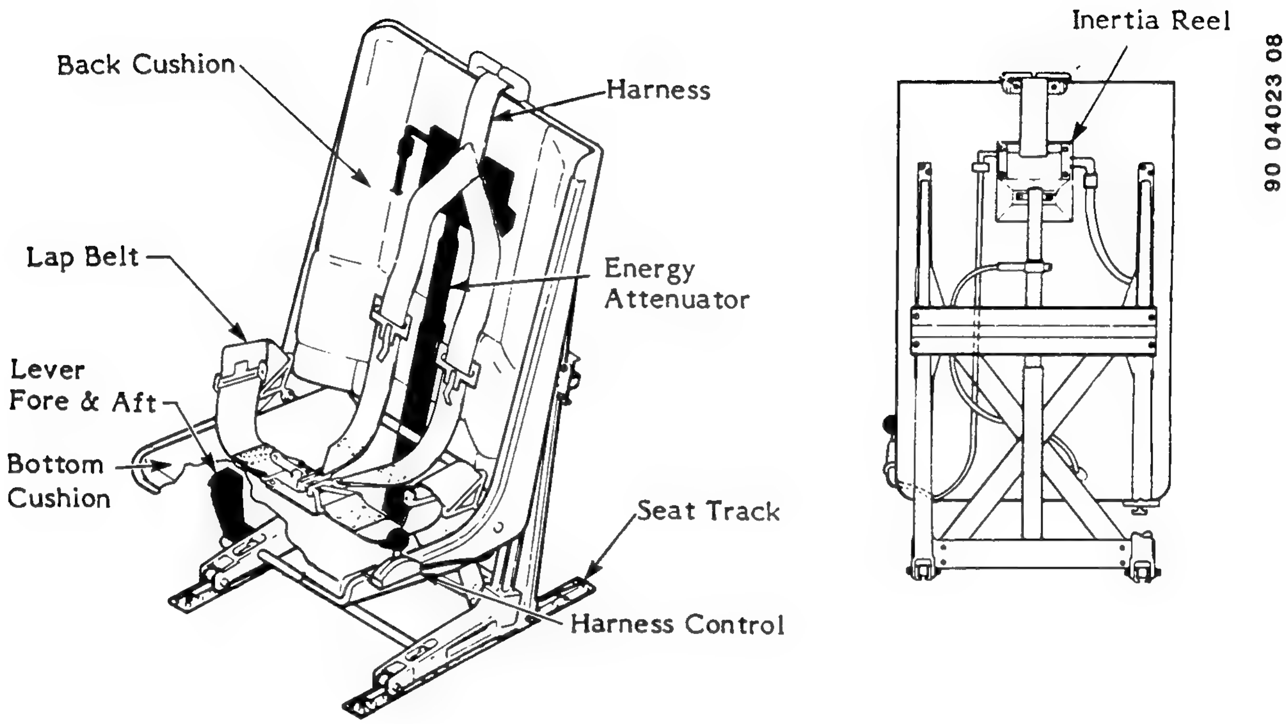

Figure C-6.
BHTI 214ST pilot/copilot seat with vertical energy absorption.

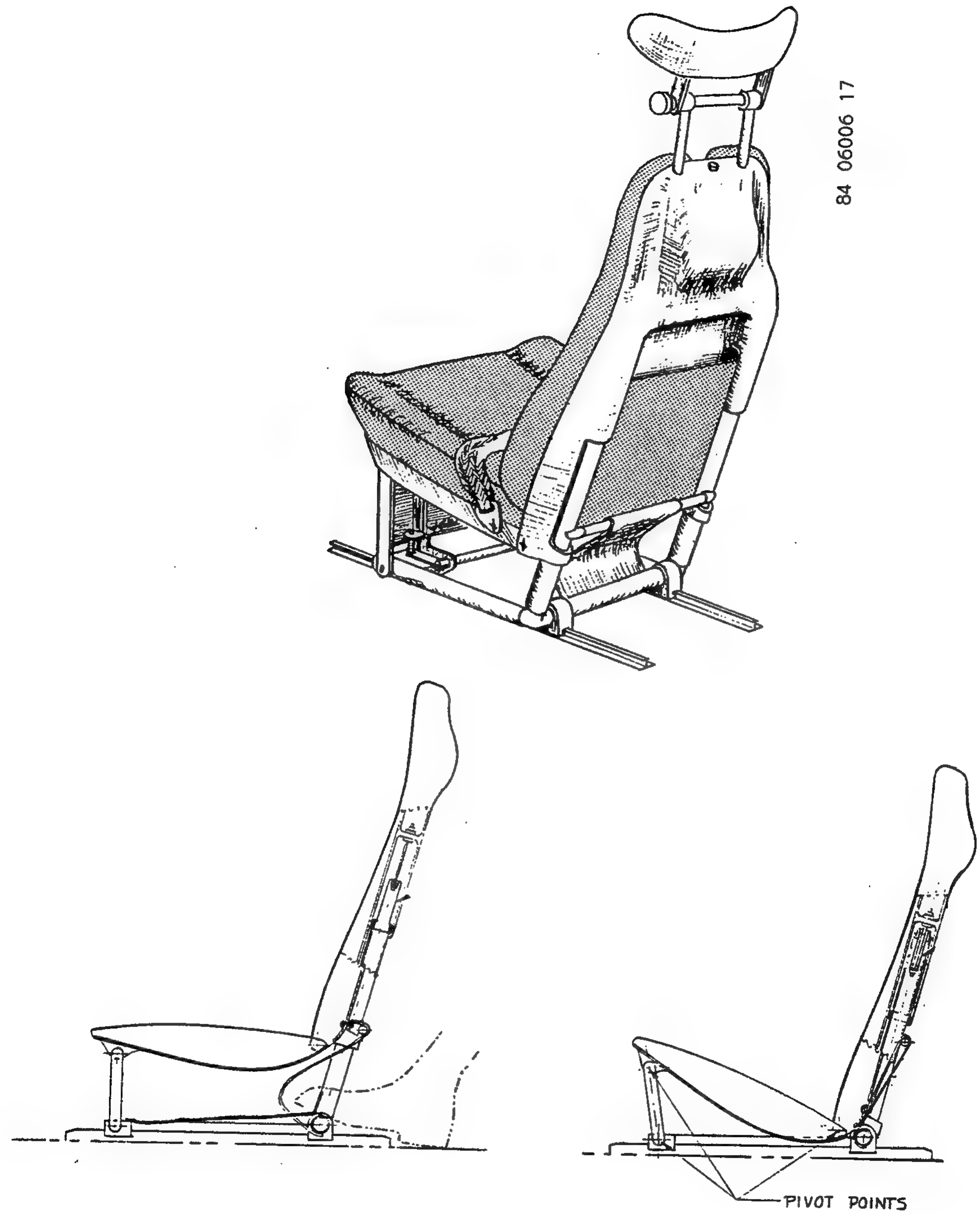

Figure C-7.
Light helicopter pilot/copilot seat concept with vertical energy absorption (Simula).

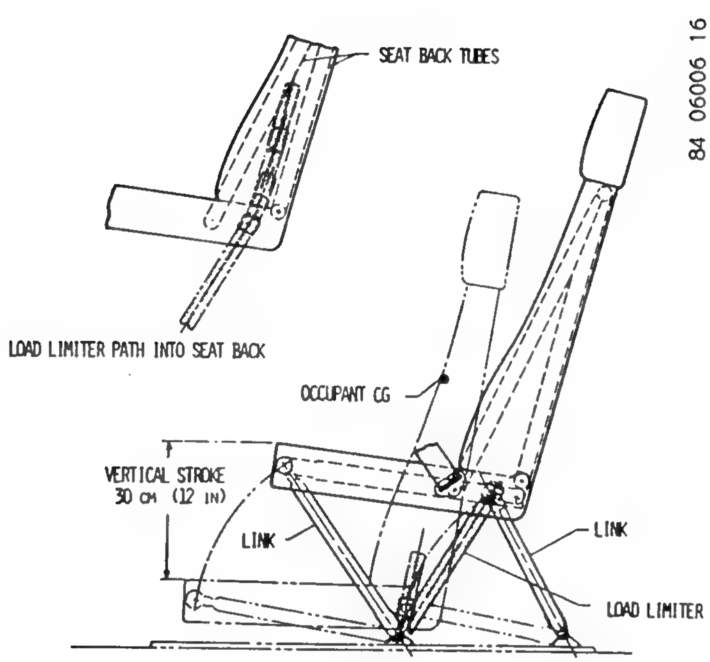

Figure C-8.
Boeing Vertol prototype seat with vertical and longitudinal energy absorption.

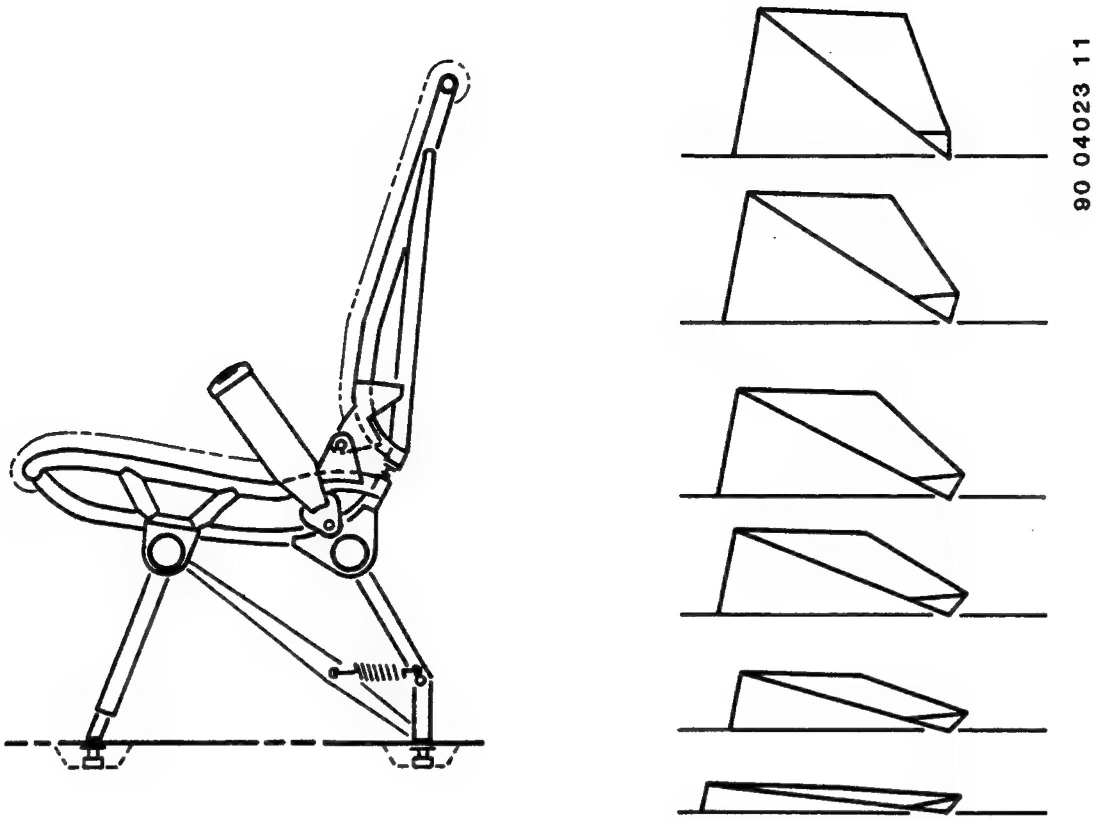

Figure C-9.
Linkage seat concept with vertical energy absorption (NASA).

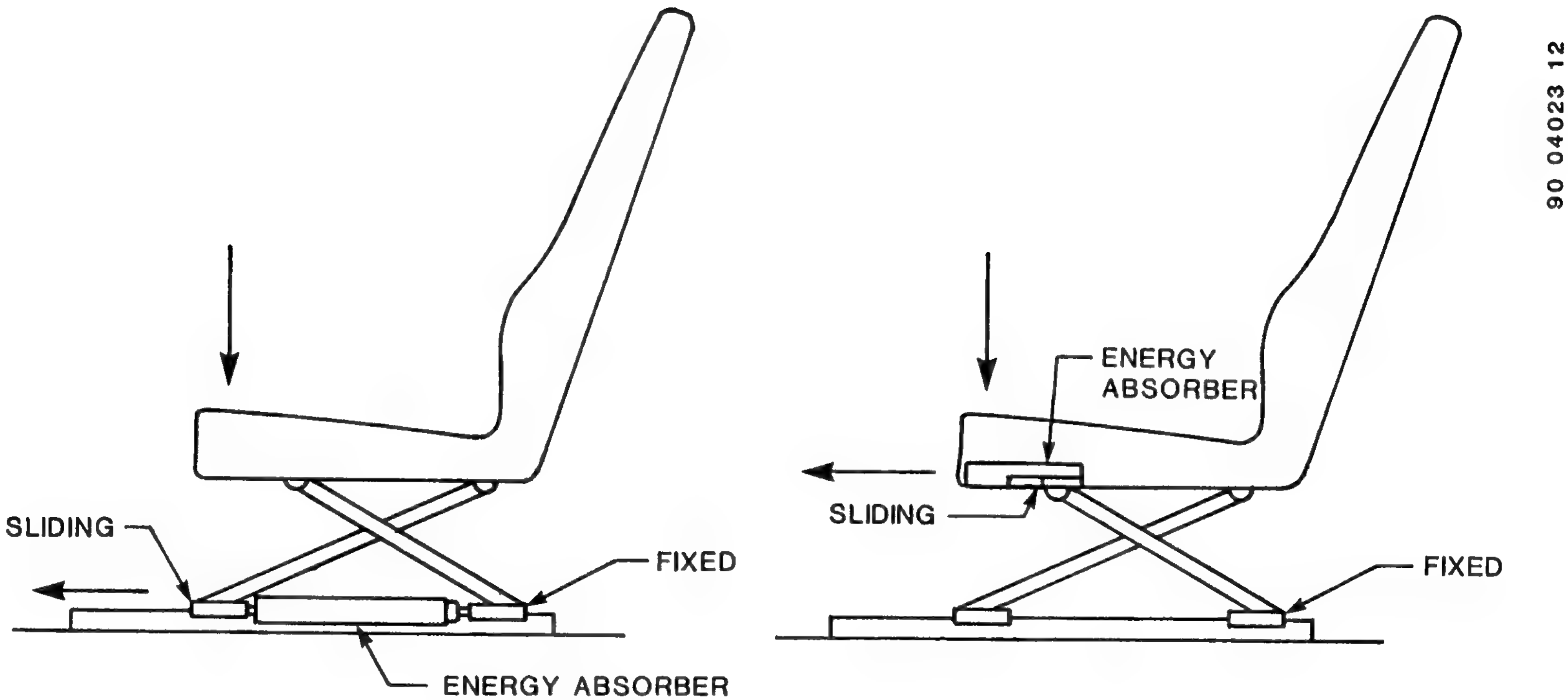

Figure C-10.
Scissor-action seat concepts with vertical energy absorption.

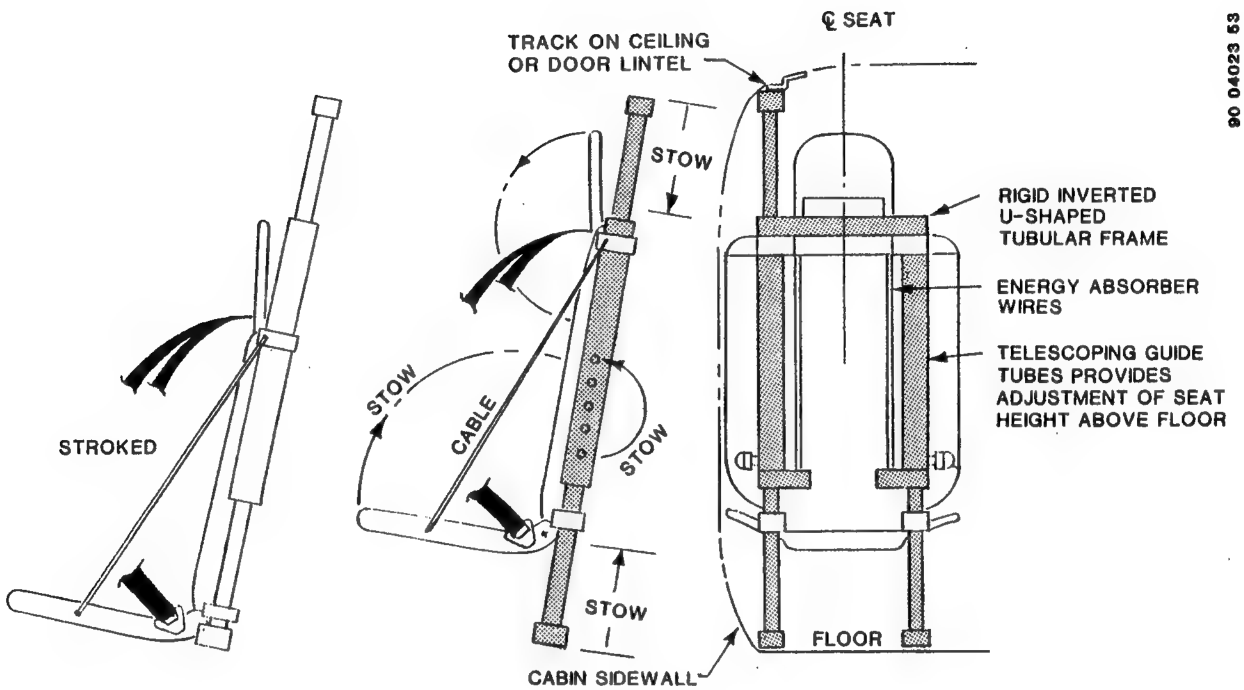

Figure C-11.
Floor-to-ceiling-mounted seat concept with vertical energy absorption (Simula).

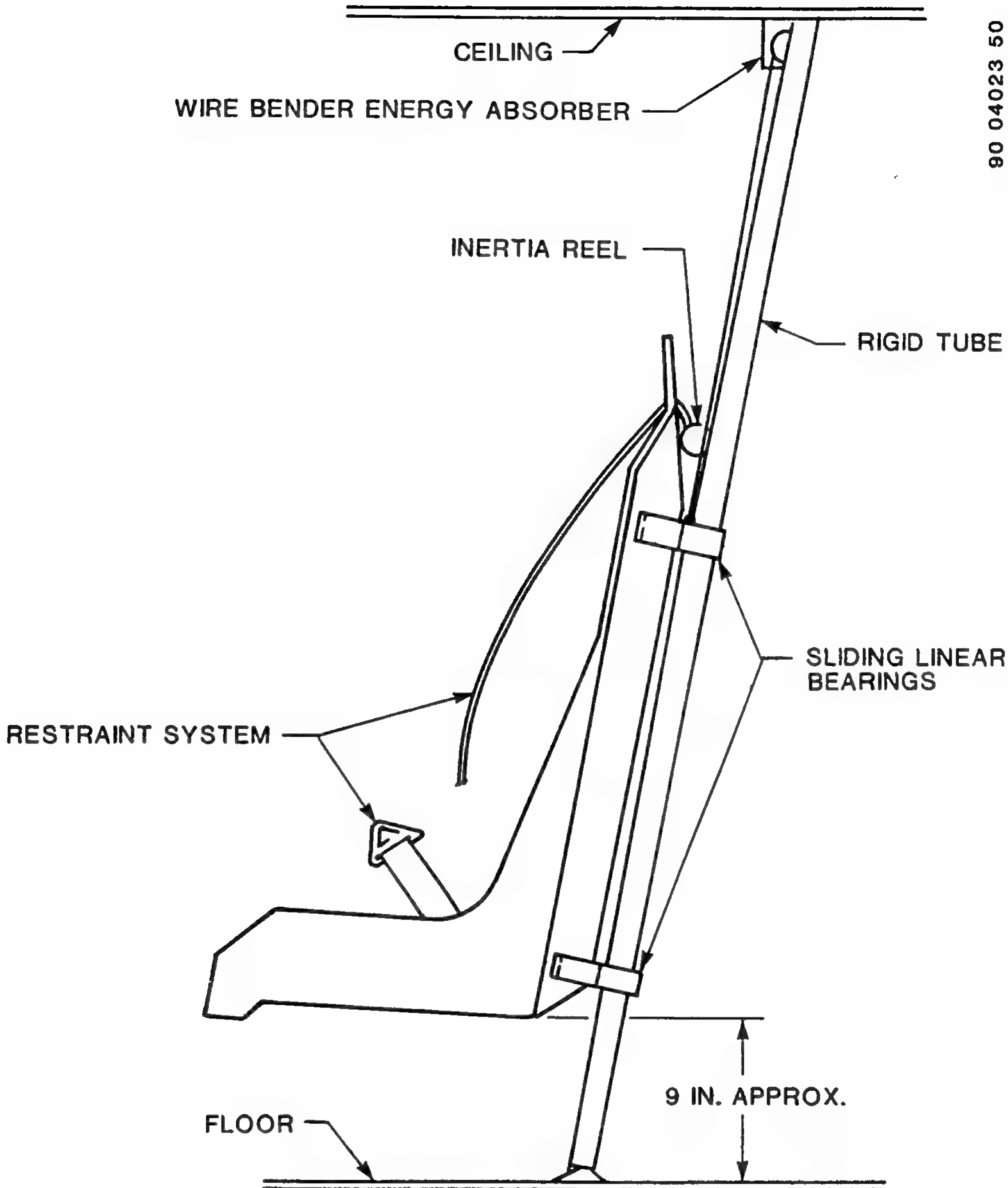

Figure C-12.
Floor-to-ceiling-mounted seat concept with vertical energy absorption (Simula).

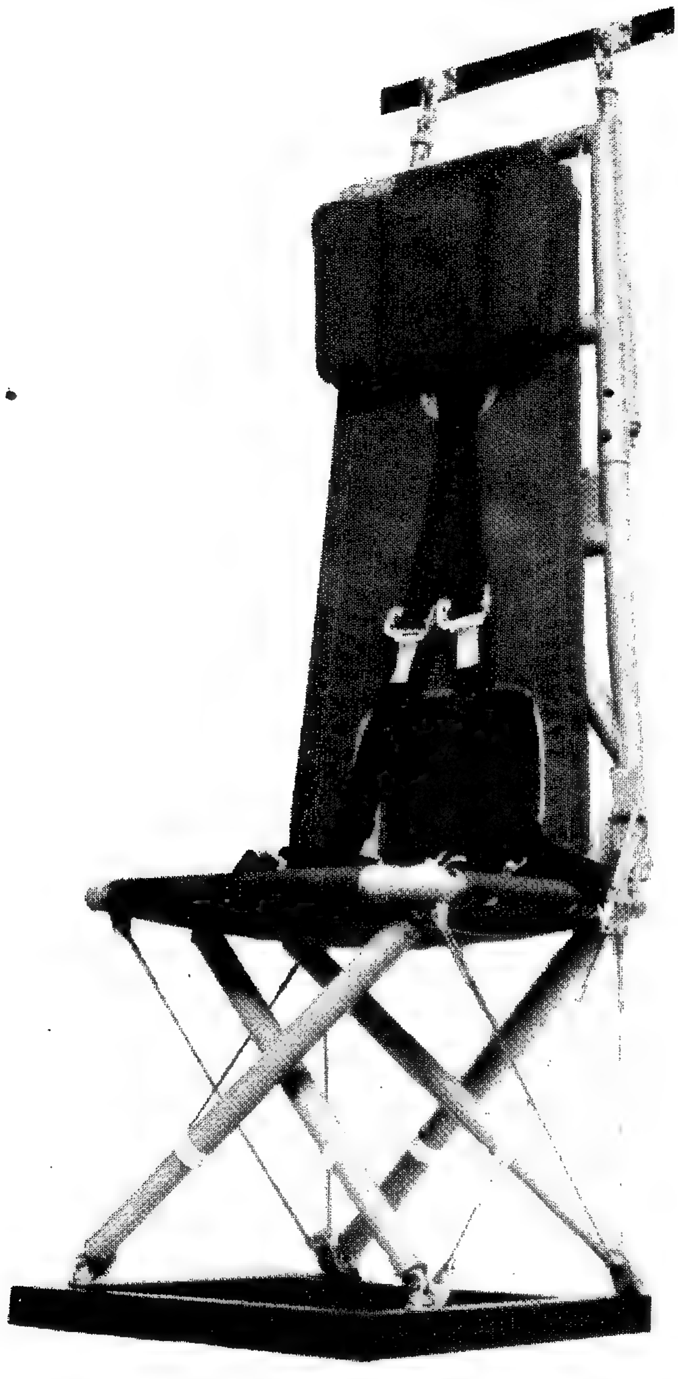

Figure C-13.
Alkan floor-to-ceiling-mounted removable seat with vertical energy absorption.

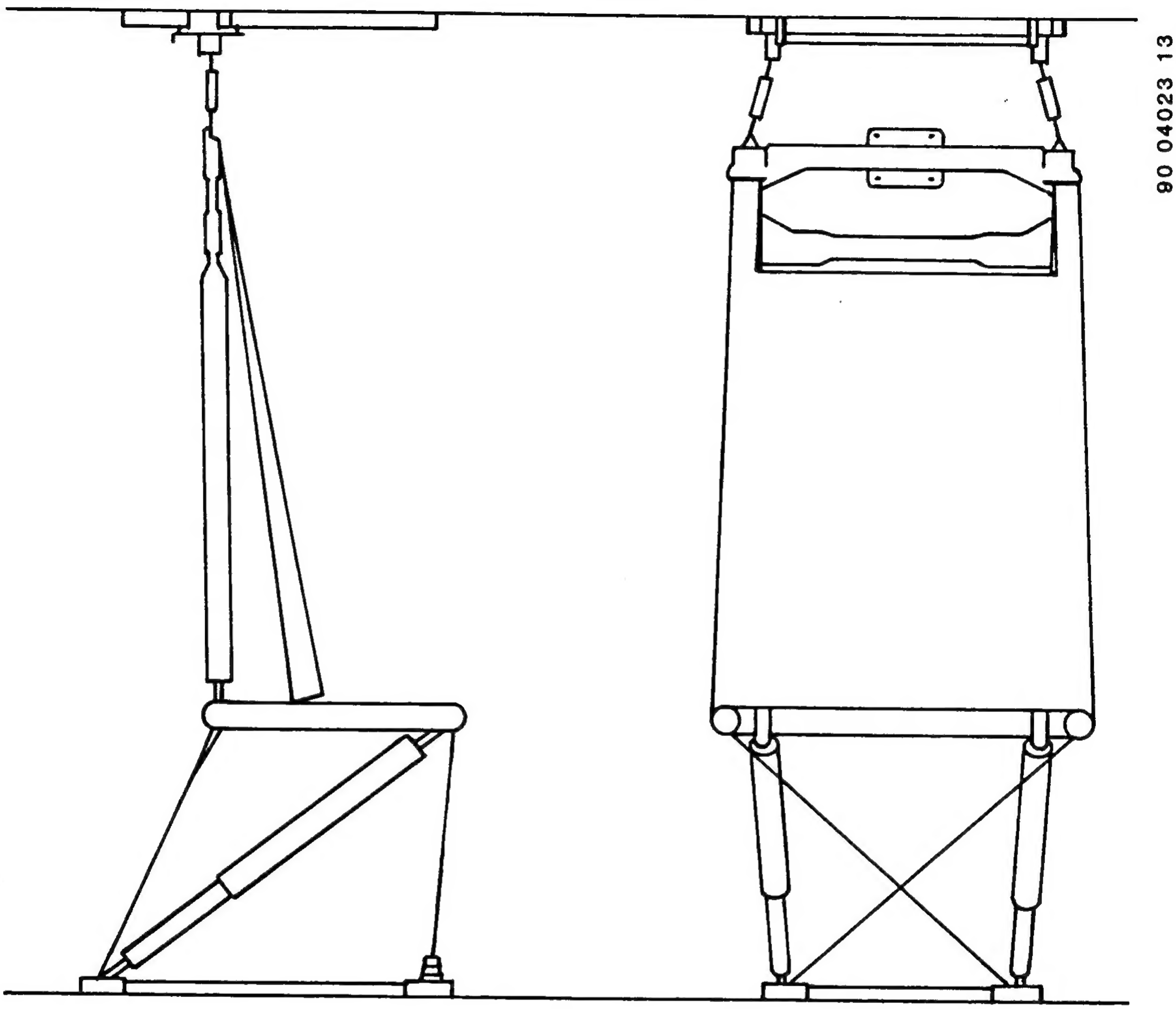

Figure C-14.
Floor-to-ceiling-mounted seat concept with vertical energy absorption (Simula).

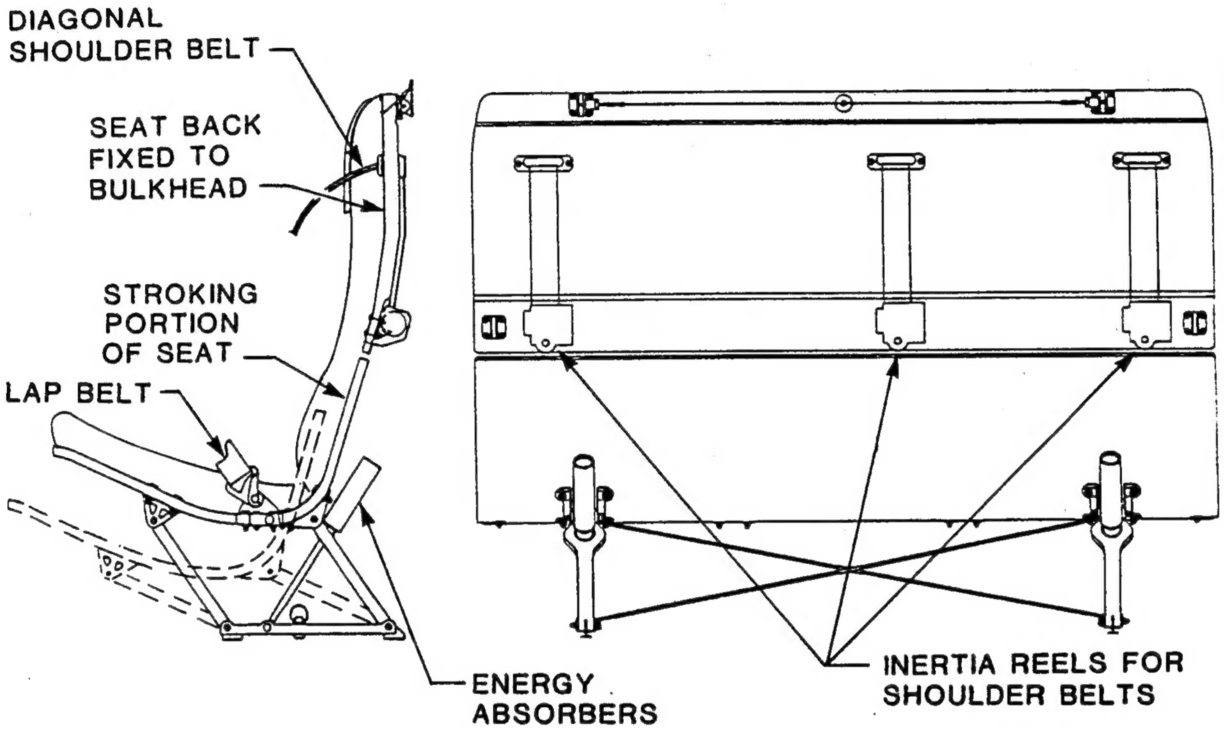

Figure C-15.
Floor- and bulkhead-mounted three-place seat concept with vertical and longitudinal energy absorption (Simula).

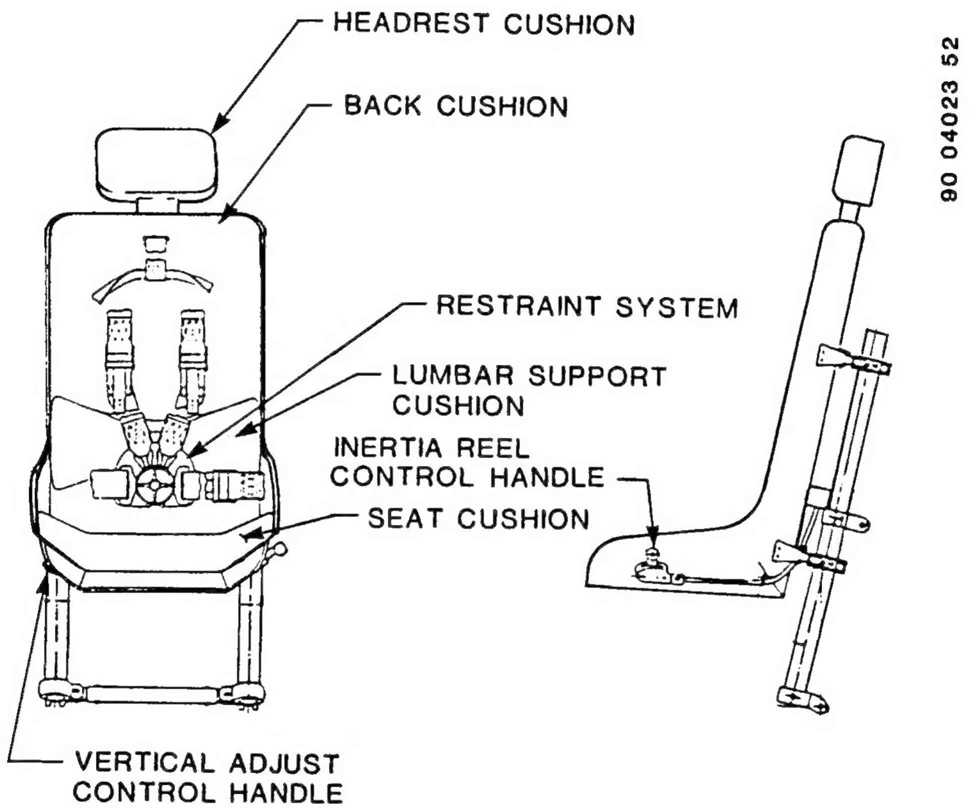

Figure C-16.
Bulkhead-mounted seat concept with vertical energy absorption (Simula).

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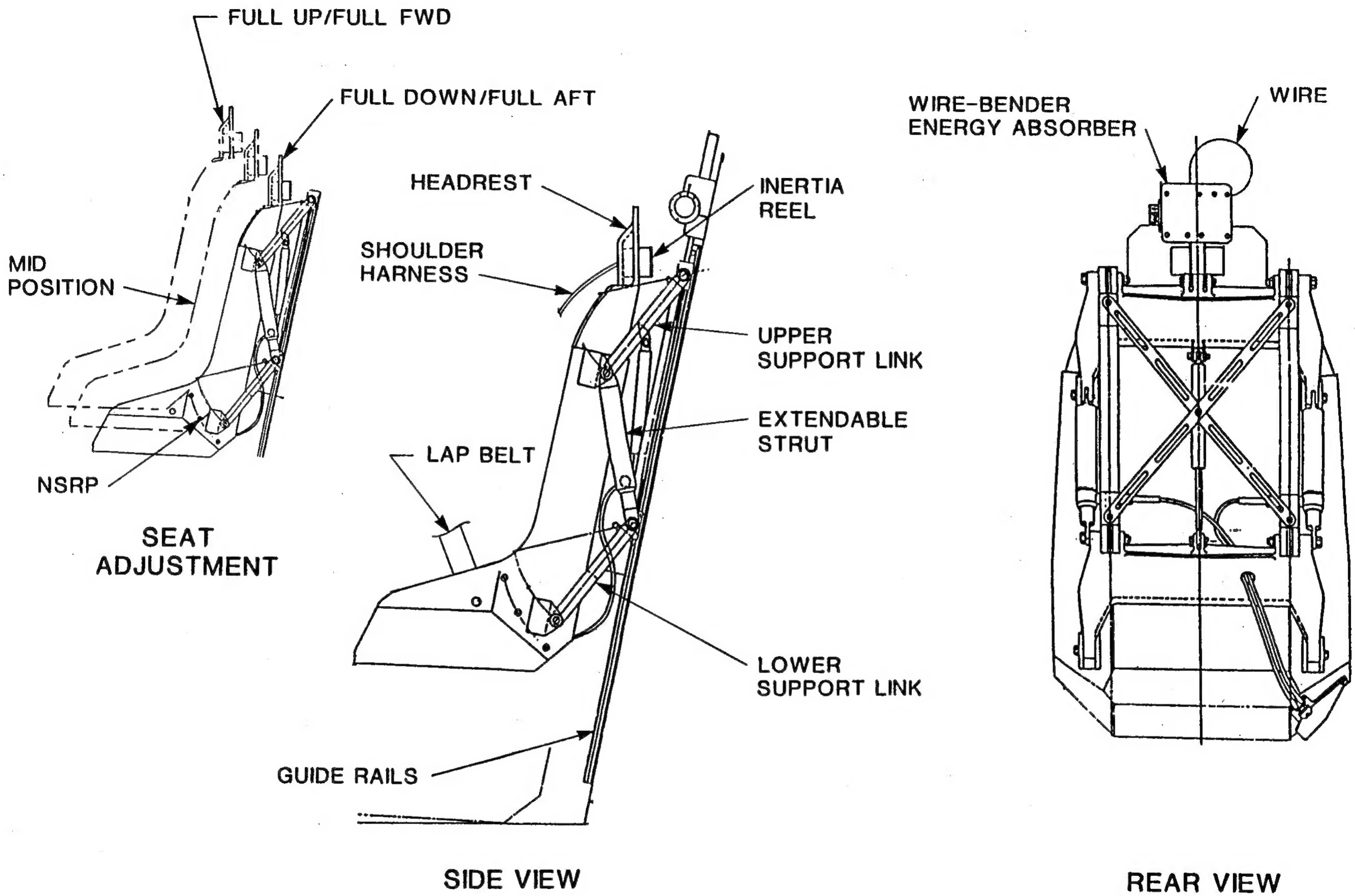

Figure C-17.
Bulkhead-mounted, scissor-action seat with vertical energy absorption (Simula).

*U.S. GOVERNMENT PRINTING OFFICE: 1994-604-081-00179